Teaching Support Pack

Graphs for Exercise Physiology

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Lecture Notes

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Acknowledgments

I would like to thank

Finally, special thanks are due to my wife for her support, encouragement, and patience throughout the time taken to bring this project to fruition.

Preface

The emphasis throughout the notes is to be as concise as clarity will allow. Much use is made of in-text tasks to encourage active involvement in the learning process. Checklists allow for the revision of all the key concepts. At the end of each section there are a selection of questions to provide practise at the level of question that candidates will meet in the external GCE examination at the end of the course, although it must be remembered that in the AEB syllabus there will be no purely biomechanical questions as such, but parts of questions relating to that particular aspect of performance.

The Review section summarises all the main concepts dealt with throughout the notes, bringing them together to emphasise the continuity of the topic. Similarly the questions at the end of this section test the candidate's overall understanding and ability to link the various principles together in an analysis of performance.

Graphs for Exercise Physiology

by Colin Clegg

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Introduction

Graphs, such as those presented here, are the simplest way of summarising the complex interactions between body systems during varying levels of activity. They allow a clear visualisation of rates of change in the activity of these systems with differing demands.

They can thus serve as excellent focus points for lectures. A consideration of the trends shown in the graphs leads naturally to a discussion of the actual physiological events underlying these trends.

The metabolic demands of the tissues, predominately the skeletal muscles in exercise physiology, stimulate corresponding changes in activity of the body systems that supply those tissues. It is important to realise and adopt this 'demand led' approach to the subject, which is also the basis of the performance based approach. By asking questions about the demands of performance, there is a natural progression to explaining the functioning of the various systems.

Exercise physiology is definitely a study of demand and supply.

Units

Special Note on units of volume

The litre *(l)* and millilitre *(ml)* are still widely used in exercise physiology, but they are not SI units, and the symbol for litres *(l)* can cause confusion eg 1.0 l. The System Internationale *(SI)* of units is intended to be used universally. Therefore the terms 'decimetre cubed' *(dm^3)* i.e. 10 cm x 10 cm x 10 cm *(1000 cm^3)* and 'centimetre cubed' (cm^3) are the more consistent and are used in all sciences, as they are here. The persistence of the litre in exercise physiology could be explained by the extensive involvement with non-science trained athletes and coaches, to whom the term decimetre cubed would be unfamiliar compared to the litre which is in common use in everyday life. A situation rather akin to the persistence of the calorie as a unit of energy in the face of the more scientifically correct SI unit the joule.

Special Note on units of oxygen uptake

Oxygen uptake is shown as VO_2. The units used can be cm^3 per minute, and may be quoted per kilogram of body weight. This can be shown as VO_2 $cm^3.min^{-1}.kg^{-1}$. Another convention is to use a dot over the V to indicate 'per minute' eg. $\dot{V}O_2$ $dm^3.kg^{-1}$ thus removing the min^{-1} from the units

Special Note on units of heart rate

Heart rate is measured as beats per minute. This is frequently and more familiarly shown as 'bpm', and more correctly as $b.min^{-1.}$ Both are used here.

Homeostasis

The fundamental principle of all physiological processes is the maintenance of homeostasis: that is a constant, optimum, internal 'steady state' essential for the maintenance of life.

In order to maintain a constant, optimum, internal 'steady state', the body must have some 'knowledge' of what the optimum 'goal state' is, against which the actual state can be compared.

In order to be aware of the actual state, there must be a sensory system capable of detecting that state; and as the body is functioning in a fluctuating environment, the sensory system must be able to detect the state of the body in the context of changing activity and external conditions.

This sensory information, or input, must be fed back to the integrating 'control centre', typically the hypothalamus of the brain, where the output is varied accordingly so that the 'goal state' may be maintained.

This input of sensory information is known as 'feedback' and the path along which it passes to the control centre is known as a 'feedback loop'.

In order to maintain a steady state, any change away from the optimum must be opposed, and this is known as negative feedback control *(positive feedback control would reinforce the change away from the steady state)*.

Continued.....

There is a delay or 'lag' in the feedback reaching the control centre, so that by the time the information reaches the control centre, conditions will already have altered, and the output is no longer entirely appropriate.

This lag results in the system 'hunting' around the optimum, so that the 'steady state' is in fact more a dynamic equilibrium within acceptable limits around an optimum.

What is a Watt?

Work rates *(power)* are quoted in watts, and although these can just be accepted as such, it is better if some understanding of the unit is achieved.

Work is measured in joules.

A joule is one newton metre.

A newton metre is the work done when the point of application of a force of one newton is moved through a distance of one metre in the direction of the force.

A newton is a measure of force required to give a mass of one kilogram an acceleration of one metre per second per second.

A watt is the unit of **rate** of work or **power**.

It is work at a rate of one joule per second.

Peak power outputs are normally measured over 1 second. Peak power outputs of about 1500 watts have been reached, but not sustained.

Power outputs are necessarily measured over a period of time. For example in an 8 s ergometer power test the subject's power output will fluctuate second by second, and by the end of the 8 s period a certain total power output will have been achieved. In this example, if the subject had been generating an average or mean power output of 500 watts per second, then the total power output for the 8 s period would have been 4000 watts. The longer the period of effort the lower will be the mean power output per second that the subject can maintain.

Continued.....

A reasonably fit person could maintain a rate of work of about 200 watts for an hour *(a total of 720 000 watts)*. Whilst Tour de France riders maintain about 250 watts for up to 7 hours.

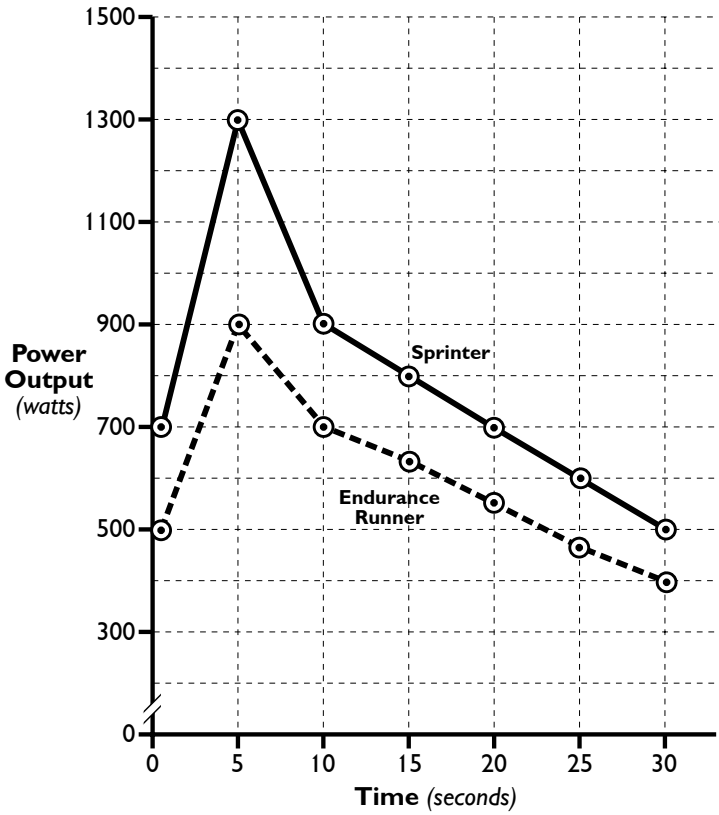
Power outputs are also quoted per kilogramme of body weight.

Some actual test results are shown below.

Sport	Mass *(kg)*	Mean power per second in an 8 second ergometer test	watts per kg
Soccer	56	411	7.34
Cyclist	75	590	7.87
Kick Boxer	76	604	7.95
Rugby Pro	79	590	7.47
Triathlon	91	604	6.64
Untrained	50	286	5.72
Judo	62	296	4.77

Power output of a sprinter and an endurance runner in a Wingate test on a cycle ergometer

Graph 1



There is no anaerobic standard comparable to that of the VO_2max of aerobic capacity. The energy requirements for high intensity 'power' exercise involve a combination of ATP/PC and lactic anaerobic, and even aerobic processes, the proportions of which vary with the intensity and duration of effort. Therefore the concepts of 'anaerobic power' or 'anaerobic capacity' are not based on sound physiological principles.

The cycle ergometer allows an easier measurement of mechanical output. However, even here mechanical factors such as pedal crank length, seat height, and inertia of the flywheel, all influence the estimation of power production on the cycle ergometer, and in measuring the power 'output' of a subject via a machine, the extrapolation to metabolic power output of the body itself is at best an estimate. Small improvements in efficiency of the machine and/or technique can significantly increase measured power output Thus, these tests are only estimating external power output, not actually measuring the capacity of the physiological processes involved.

Continued.....

The Wingate Test involves a 30 second flat out effort on a cycle ergometer against a resistance calculated with respect to body weight in kg.

The power profile is recorded and plotted against time. The maximum anaerobic power is usually reached before about 5 seconds, and is generated by the **alactic anaerobic** ATP/PC system.

Over the 30 second period of flat out effort there is a progressive depletion of the alactic anaerobic ATP/PC system, and an increasing involvement of the lactic anaerobic system. Because of the overlapping involvement of the anaerobic systems they cannot be clearly separated, but the average power over the 30 second period of exercise is taken as an indicator of the lactic anaerobic power which is calculated per kilogram of body mass. However, it must be remembered that 30 seconds will not exhaust the anaerobic capacity, an important ATP/PC component is also involved, and about 20% of the total energy production during a 30 second Wingate Test is aerobic.

It is important during the warm-up that subjects perform several flat-out sprints to establish a state of readiness and to ensure that they are aware of the 'feel' of the effort involved. Failure to practice in this way often leads to the initial effort being restricted, so that when the subject realises s/he kicks harder towards the end. This means that peak anaerobic power is reached later than anticipated and the extent of power decline is less than it might otherwise be.

During the test, watts should be recorded at 5 second intervals so that power decline can be plotted against time. This will help to check that the test was carried out properly. If it was, there should be a smooth steady decline after an early peak. Any change in the rate of decline might mean that the subject has either checked or increased his/her effort during the test which will affect the end result.

If the oxygen uptake during the period of exercise can be measured, then the oxygen deficit can be calculated, and used to determine the anaerobic energy yield.

The progressive power decline can be calculated from the formula:

$$\text{Power decline} = \frac{\text{Peak power} - \text{End power}}{\text{Peak power}} \times 100$$

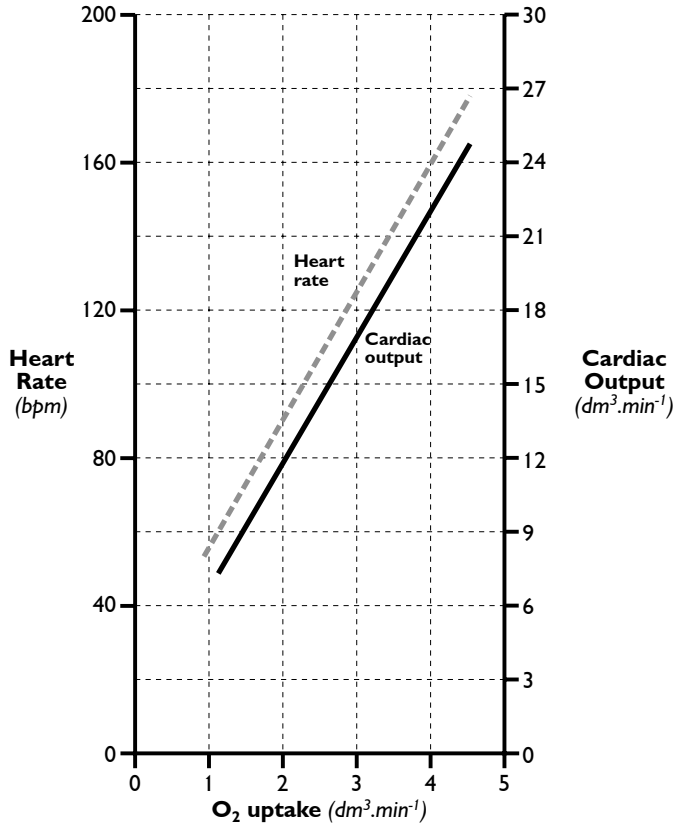
The power decline is a measure of fatigue and can be used to calculate a fatigue index, using the formula:

$$\text{Fatigue index} = \frac{\text{Power decline}}{\text{Time between peak and end power in seconds}}$$

A repeat test five minutes later, can give a measure of the repeat capacity, important to games players.

Ideal linear relationship between heart rate and oxygen uptake, and cardiac output and oxygen uptake, at sub-maximal work rates

Graph 2



The contracting skeletal muscles consume oxygen in aerobic respiration to supply energy in the form of ATP for the sliding filament mechanism. Initially this oxygen will be obtained from the oxymyoglobin in the muscle fibres themselves, but as demand is sustained or increased the oxygen diffusion gradient between the muscle fibres and the oxyhaemoglobin in the red blood corpuscles 'steepens' ie becomes greater, and the oxyhaemoglobin dissociates to release its oxygen to the plasma and then the tissue fluid.

This demand for oxygen is associated with a corresponding production of carbon dioxide, which by forming hydrogen carbonate ions in the plasma, the form in which the majority of carbon dioxide is transported in the blood, assists in the dissociation of oxyhaemoglobin.

Continued.....

Except at low oxygen partial pressures, the increase in breathing and heart rate seen in exercise of a certain intensity is proportional to the amount of carbon dioxide produced by the tissues *(and other metabolites eg lactate, potassium ions etc)*, which in aerobic respiration is in turn proportional to the oxygen demand of the tissues.

Thus the heart rate increases proportionally in order to increase the cardiac output to increase the circulation of the blood between the tissues, where the demand originates, and the lungs where the oxygen is supplied *(and the carbon dioxide excreted)*.

At the lungs, a larger volume of partially deoxygenated blood flows more rapidly through the pulmonary circulation with a steeper oxygen diffusion gradient *(and carbon dioxide gradient)*, resulting in a greater oxygen uptake *(and carbon dioxide excretion)*.

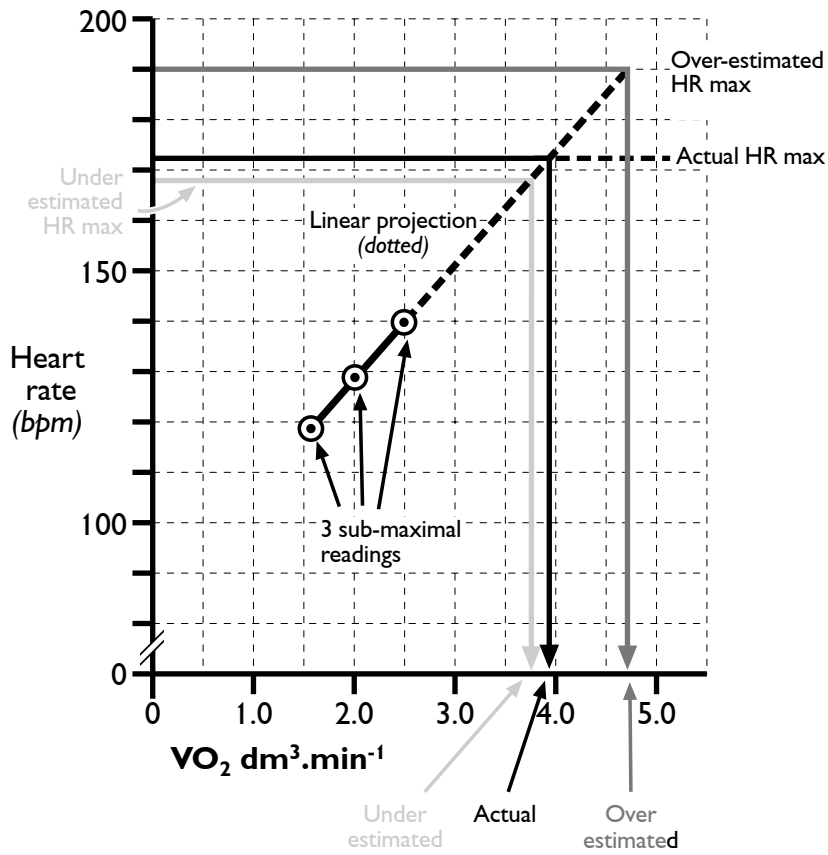
At sub-maximal work rates, the heart rate is generally proportional to the cardiac output

So the simple straight line relationship between heart rate and cardiac output on the one hand, and the oxygen uptake on the other can be understood.

At maximum work rates however this simple straight line relationship is lost.

Projection of maximum oxygen uptake from heart rates in a progressive incremental sub-maximal test

Graph 3



The projection of maximum oxygen uptake from sub-maximal heart rates depends for its accuracy on the linear relationship between heart rate and oxygen uptake in sub-maximal exercise, and the correct estimate of maximum heart rate.

Maximum heart rate is very difficult to establish with any degree of consistency. It can vary according to type of exercise, degree of motivation, state of fitness, and a host of other changing circumstances that can vary from day to day.

The commonest used estimate is that of 220 minus your age.

As can be seen if the maximum heart rate is underestimated the projected maximum oxygen uptake will be underestimated, and if the maximum heart rate is overestimated the projected maximum oxygen uptake will be overestimated.

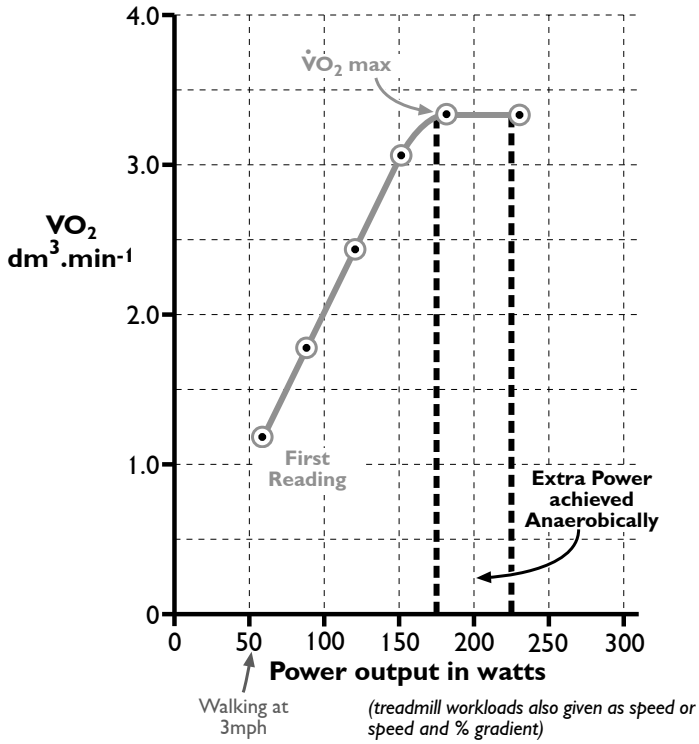
Continued.....

As with all projections a small change in the gradient of the line from which the projection is to be made will result in a much larger difference in the projection.

It is also known that the heart rate/VO_2 relationship plateaus near the maximum, so that a linear projection leads to underestimation of VO_2.

Oxygen uptake in relation to work output in a progressive maximal test

Graph 4



2 minutes at 60 watts and then increments of 30 watts every 2 minutes.
A watt is the unit of rate of work or power 1w = $1J.s^{-1}$.
A reasonably fit person could maintain about 200 watts for an hour.
Tour de France riders maintain about 250 watts for seven hours.
Peak power outputs are as high as 1500 watts.

At sub-maximal work rates oxygen uptake is proportional to work rate. As the work rate goes up, the demands of the active muscle tissue goes up, and the increased demand is met by a proportional increase in supply of oxygen via an increase in heart rate and cardiac output.

However, at high work rates, the work rate continues to increase without a proportional rise in oxygen uptake; in other words the curve 'flattens out'.

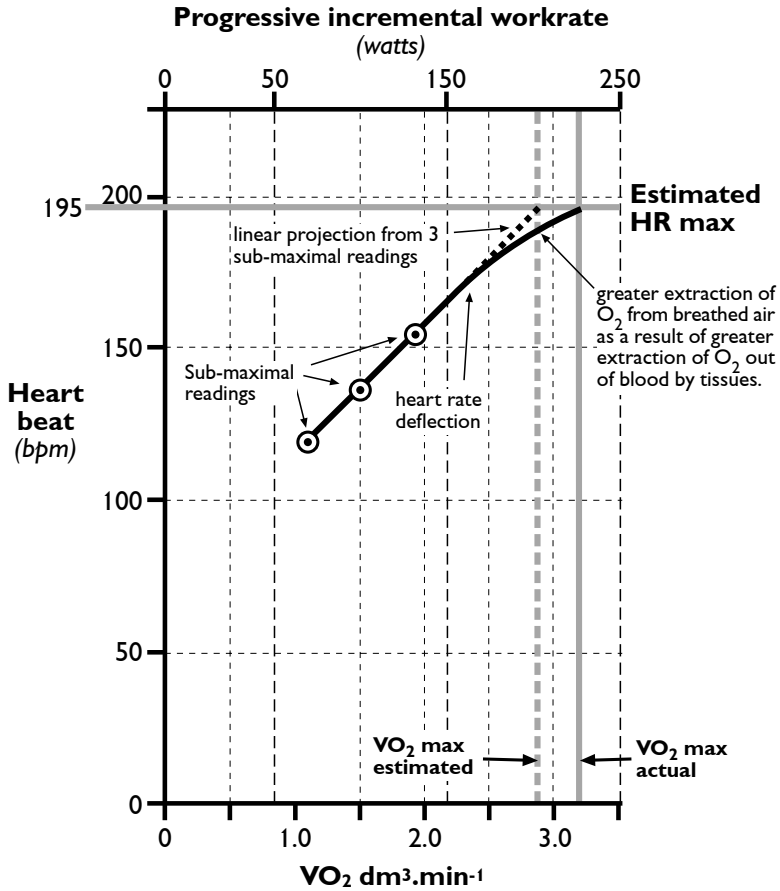
The additional energy for these very high work rates is supplied independently of that supplied aerobically using the oxygen taken up at the lungs, eg by an increase in the rate of anaerobic respiration.

It is interesting to note from this graph that a maximal test is not necessary for the assessment of maximum aerobic power or VO_2 max, only the achievement of a 'plateau' of readings of oxygen uptake, which as is seen in the graph may occur below the maximum work rate.

In practice, subjects usually work to volitional exhaustion, as the plateau may be more a decline in the rate of increase of VO_2 and quite difficult to spot during the test.

The relationship between heart rate, work rate, and oxygen uptake during progressive incremental maximal testing

Graph 5



The straight line or linear relationship between heart rate and oxygen uptake at sub-maximal work rates is fairly consistent, and used for projections of the maximum oxygen uptake on the basis of the estimated maximum heart rate.

Projections made from such sub-maximal readings on the basis of the estimated maximum heart rate can underestimate the maximum oxygen uptake, as the linear relationship is lost at higher work rates at the heart rate deflection point.

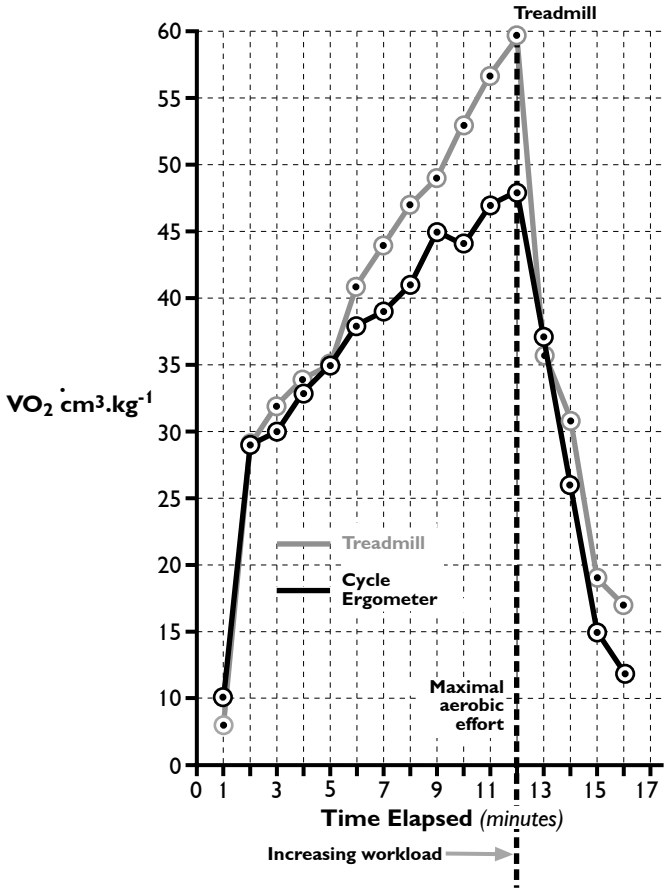
This heart rate deflection point has been used as a method of estimating the lactate threshold on the basis of the work rate eg running speed *(Conconi)*, but this correlation is questioned by many who report that the heart rate deflection point occurs at a much higher work rate than the lactate threshold.

Continued.....

As the subject nears their maximum work rate, the oxygen uptake increases proportionally faster than the heart rate, as more and more oxygen is extracted from the blood by the near maximally working muscle tissue, steepening the oxygen diffusion gradient between the alveolar air and pulmonary capillaries.

Oxygen uptake against time in a single subject during a progressive maximal test on *(i)* a treadmill; and *(ii)* a cycle ergometer.

Graph 6



These curves are those of an actual subject under test, and this explains the non-ideal nature of the curves. Elsewhere, stylised curves are presented which show 'classic' straight line *(linear)* relationships between various parameters in sub-maximal tests, and various other smooth curves for the upper limits of maximal tests.

It is a good idea at the outset, to establish in the student's mind that ultimately all knowledge of 'exercise physiology' is derived from actual measurement. Admittedly, some informed conjecture and extrapolation is also involved, eg about the precise events in the muscle tissue with regard to the use of the various energy systems, but even these intelligent 'guesses' are based on experimental data, and are continually revised in the light of on-going research.

Continued.....

The main point of interest here is the disparity between the two curves. A single athlete is under test, and if tests such as those carried out on the treadmill and cycle ergometer are valid, then one would expect similar results on both.

As can be seen, in fact tests are specific to the activity on which they are based. In this case the subjest was a middle distance runner, and it would be reasonable
to assume that he was capable of getting closer to his maximum in his own discipline.

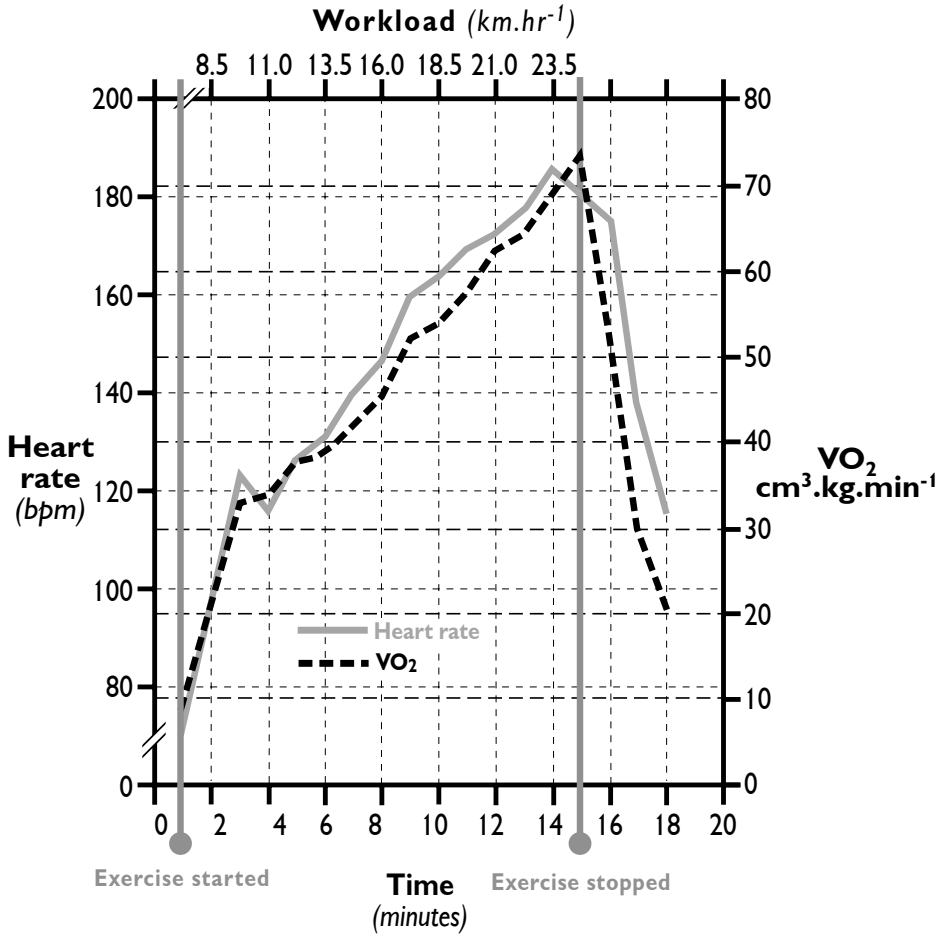
However, it is also true that treadmill tests consistently give higher readings than the cycle ergometer, due to the greater musculature involved in an activity that involves supporting the body weight on the legs, and also involves active movement of the upper body such as running, resulting in a greater oxygen uptake for a given effort.

Even though these were meant to be maximal tests, as no plateau of oxygen uptake was achieved, they have determined the '**peak oxygen uptake**' and not the 'maximum oxygen uptake' as such.

The recovery period is of interest with respect to the excess post-exercise oxygen uptake or EPOC.

Heart rate and oxygen uptake against time of a middle distance runner during a progressive maximal treadmill test

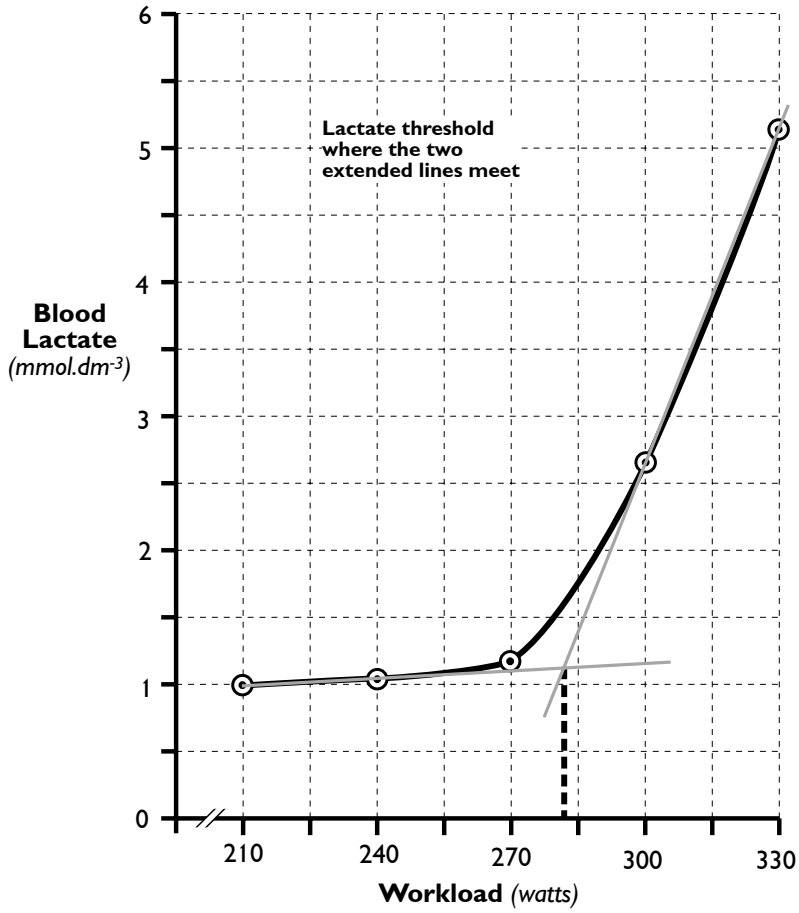
Graph 7


Workload (km.hr-1)
8.5 11.0 13.5 16.0 18.5 21.0 23.5
Heart rate (bpm)
VO2 cm3.kg.min-1
200 180 160 140 120 100 80 0
80 70 60 50 40 30 20 10 0
Heart rate
VO2
0 2 4 6 8 10 12 14 16 18 20
Exercise started
Time (minutes)
Exercise stopped

These two graphs both show the 'non-ideal' curves derived from actual laboratory measurements. Not much can be deduced from the various fluctuations away from the ideal, although observations around the peaks are of interest.

Determination of Lactate Threshold in a progressive incremental test by projection

Graph 8



The concept of 'lactate threshold' is still a contentious issue. Lactate is produced on a continuous basis and the choice of a 'threshold' is necessarily arbitrary. However, this method identifies a specific point at which there is a distinct increase in the lactate accumulating in the blood.

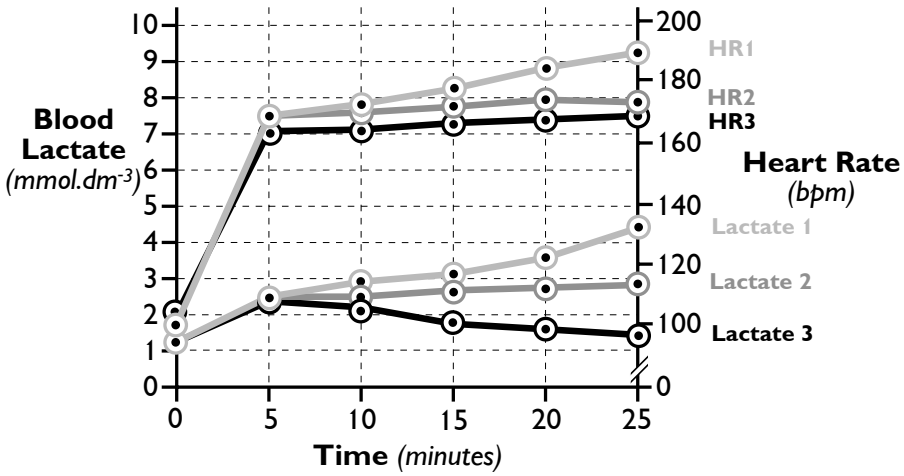
In this case it has been reckoned by drawing tangents from the two 'straight' segments of the curve - the 'threshold' being taken as the point of intersection. As can be seen the choice of the two tangents is crucial, and small variations in slope will alter the point of 'threshold'.

Although it can vary from day to day in a single athlete, the establishment of a lactate threshold is useful for establishing 'training zones' in relation to the 'threshold'. These sessions are efficient in the sense that they can focus on one zone or the other, or on a mixture of both if so required.

A trained athlete should be able to work for about 50 - 60 minutes at or just below LT. In running this would mean a pace that was sustainable for about 10 miles.

Determination of Maximum Lactate Steady State in a progressive incremental test

Graph 9



Progressive Incremental Work Load	Time in minutes	0.0	5.0	10.0	15.0	20.0	25.0
Load 1	Lactate 1	1.31	2.49	2.50	2.67	2.72	2.80
	HR 1	100	169	171	173	174	173
Load 2	Lactate 2	1.31	2.50	2.90	3.10	3.54	4.36
	HR 2	104	170	173	178	185	190
Load 3	Lactate 3	1.31	2.40	2.22	1.80	1.60	1.40
	HR 3	104	166	165	167	168	169

Having established an idea of the lactate threshold of a subject, several work load regimes are devised just above and below the threshold load.

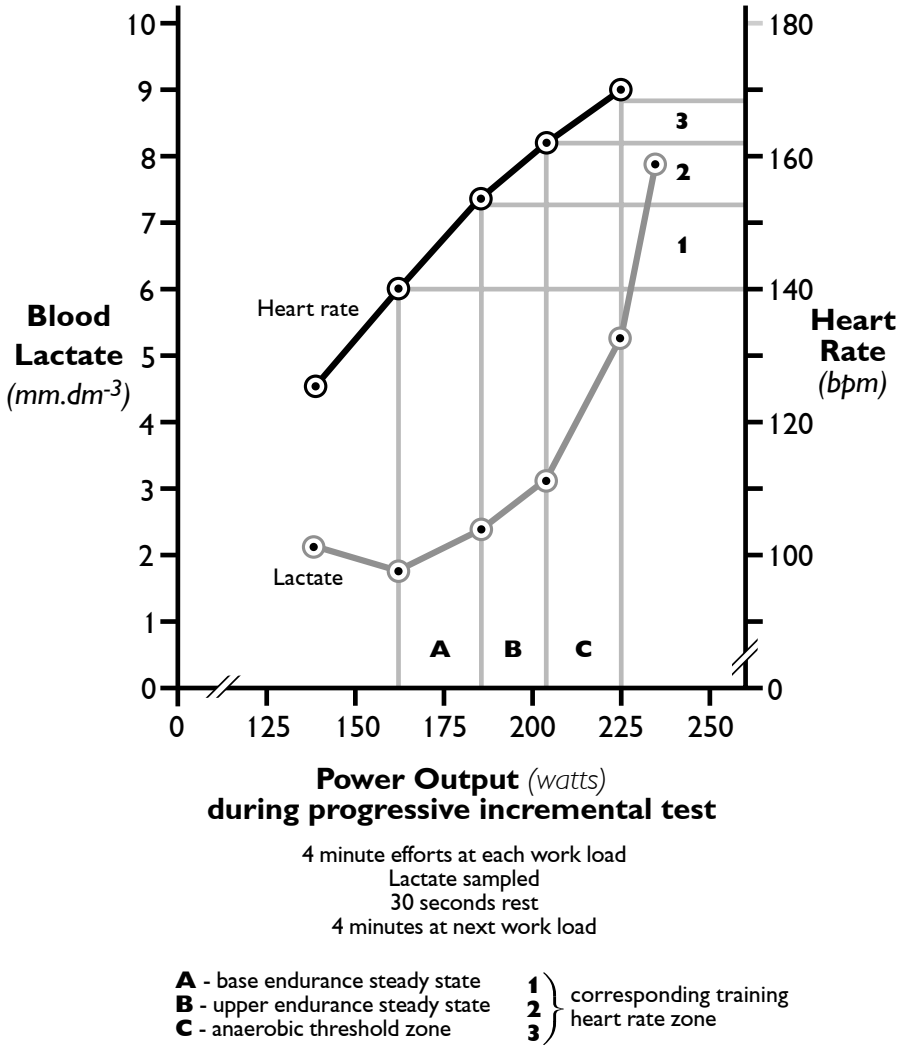
If the load is too high, the level of lactate will rise continuously throughout the test, as seen in the curve marked 'Lactate 1', if too low then the level of lactate will drop throughout the test as aerobic processes adapt, become the main source of energy, and effect the gradual removal of lactate, as seen in the curve marked 'Lactate 3'.

At the 'right' work load the lactate will rise, and remain steady for the duration of the test, as seen in the curve marked 'Lactate 2'.

This is useful when designing training sessions of optimum intensity.

Determination of heart rate training zones from blood lactate measurements during progressive incremental work loads

Graph 10



By measuring the increase in lactate and heart rate during a progressive incremental test it is possible to determine recommended training heart rate zones to achieve specific training objectives.

However, the changes are continuous and the 'steps' are not always as clear as shown in this example, therefore there is always a degree of judgement in deciding where to draw the limits of the three 'zones'.

Continued.....

The use of these three zones in a training programme for a runner could for example be as shown below.

Level 1 Improves ability to use fat reserves and 'spare' glycogen.
Involves long easy sessions of light rhythmic exercise.
No audible breathing;
otherwise not an efficient use of training time except for preparation for events longer than 2.5 hours, or as active 'recovery'.

Level 2 Improves VO_2max.
Involves steady running for up to 90 mins, whilst conscious of breathing not being out of breath;
intensity is just below LT;
heart rate can 'drift' up due to a reduced blood volume as a result of dehydration, or increased body temperature if not adequately cooled.

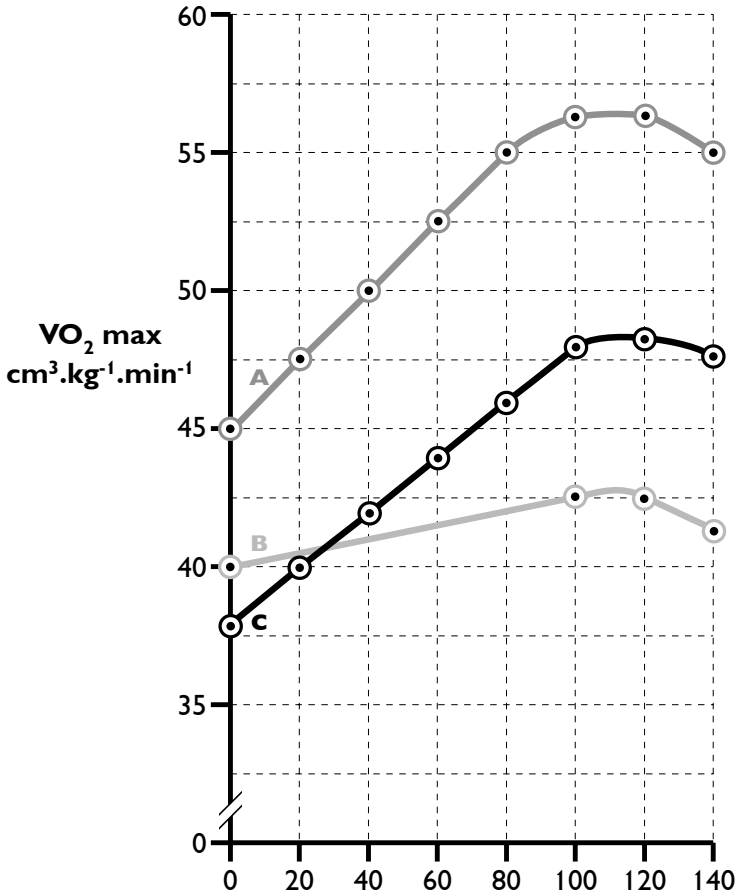
Level 3 Improves % VO_2max that can be sustained for longer periods.
Involves 'heavy breathing' sessions that are just sustainable for 20-30 mins;
or intervals of 5-15 mins with 2-5 mins jog recovery intervals;

Others identify a further level of intensity, Level 4.

Level 4 Improves anaerobic capacity, and components of VO_2max *(eg. stroke volume)*.
Involves 'very heavy breathing' high intensity work over periods of less than 5 minutes;
short recovery intervals.

The effect of endurance training on maximal oxygen uptake

Graph 11



The arguments about the trainability and consequently the inheritability of maximal oxygen uptake are still far from resolved.

Sportspeople themselves often claim their success to be the result of varying combinations of their ambition *("I wanted it more")*, dedication *("I train harder")*, way of life *("I eat healthily")*, training schedules, coach, childhood background *("Kenyans and Ethiopians run to school")*, and many more. Very seldom do you hear "I have made the most of my exceptional inherited gifts, which gave me the platform for my achievements."

Textbook estimates of the trainability of maximal oxygen uptake vary considerably. The inference being that the remainder is due to heredity

Continued.....

The figures indicate that runner A would most likely be of good club standard, and runners B and C of an average standard; although maximal oxygen uptake is not a good predictor of performance on its own.

The graph presented only shows the results of three runners, and as such proves nothing, but it does raise interesting points for discussion on this subject.

The similarity in shape of the curves certainly indicates similar underlying processes.

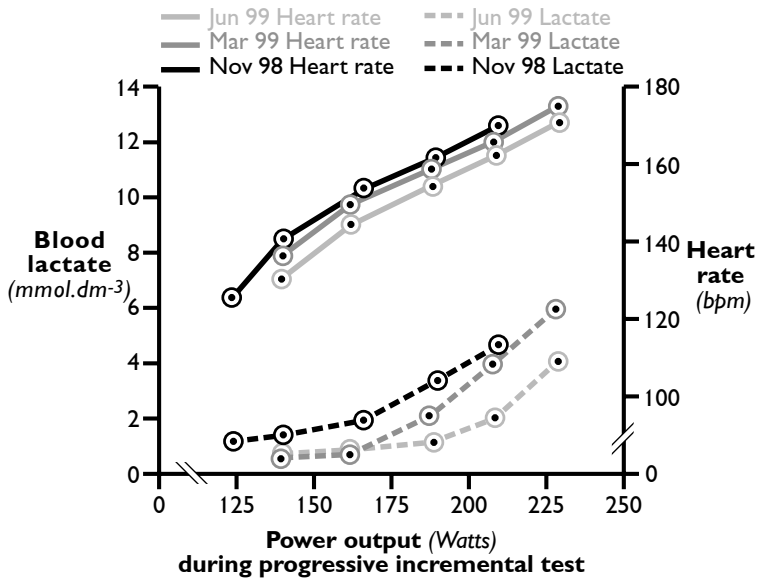
The effect of diminishing returns is well illustrated, as none of the athletes continues to improve with increasing training distance beyond 100 km per week. All maximal oxygen uptakes plateau out, and in fact begin to decline as the training distance reaches a maximum. The decline indicating the effects of overtraining and excessive fatigue.

This observation reinforces the almost universally held view that quality is more effective than quantity in all training regimes.

The situation with regard to runner B indicates that, all other things being equal, the ability to improve with training may itself be strongly influenced by hereditary. Runner B would appear to be a so-called 'non-responder', not making the gains with training that might ordinarily be expected.

Fitness progression of an athlete as measured at 3 monthly intervals

Graph 12



Step Test	Workload	1	2	3	4	5
Jun 99	Watts	140	162	188	208	228
	Lactate	0.70	0.90	1.20	2.06	4.09
	Heart rate	131	145	155	163	171
Mar 99	Watts	140	162	188	208	228
	Lactate	0.60	0.70	2.11	3.92	6.00
	Heart rate	137	150	159	166	175
Nov 98	Watts	124	140	166	189	209
	Lactate	1.22	1.49	2.00	3.40	4.70
	Heart rate	126	141	154	162	170

4 min efforts at each workload, lactate sampled, 30 sec rest, 4 min at next workload....

There is a clear correlation between the progression shown in the decrease in heart rate and the delay in the increase of blood lactate at a given work load.

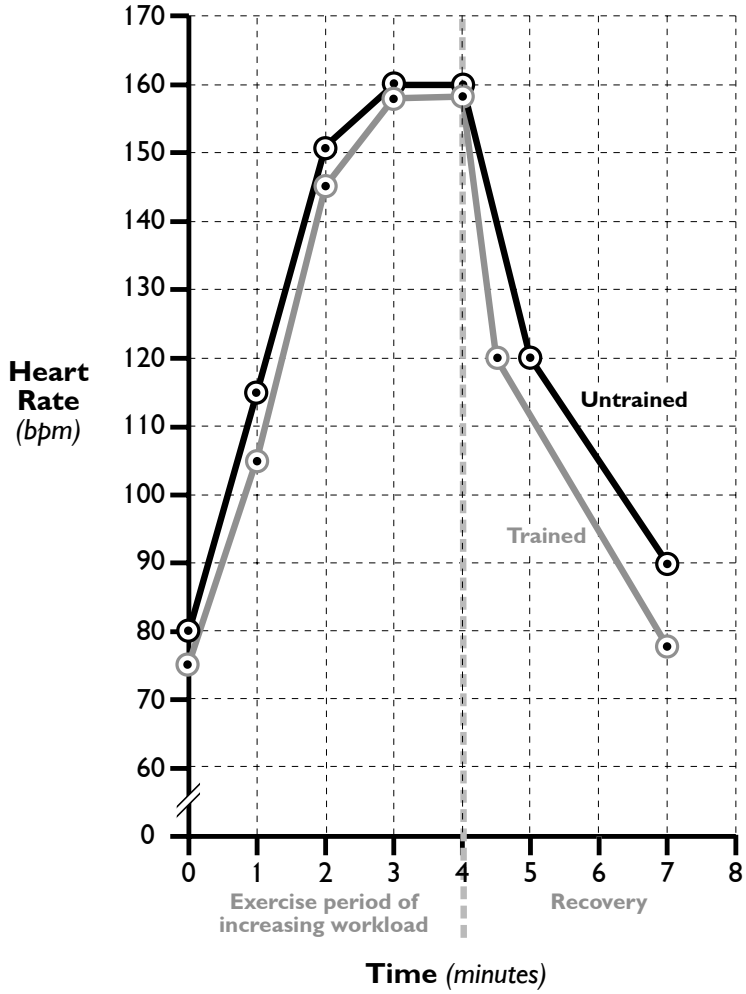
Over the period shown the heart rate decreases over the range of all work loads as the heart shows adaptations to the training, eg increased contractility increasing the ejection fraction and thus the cardiac output, and even an increase in the diastolic end volume of the ventricles.

A similar progression can be observed in the blood lactate levels, with the power at threshold being raised from about 160 watts to about 200 watts. These changes reflect the increase in efficiency of the aerobic systems which delay the onset of the accumulation of lactate in the blood.

Although they will only be a part of the continual monitoring that physiologist, coach and athlete carry out *(much of it subjective)*, these curves give clear objective feedback to coach and athlete about the rate of progress or otherwise.

Effect of training on post-exercise recovery heart rates in a single subject

Graph 13



An average healthy but untrained male underwent a progressive ramp protocol sub-maximal 4 minute treadmill test, before and after a 6 week aerobic training period.

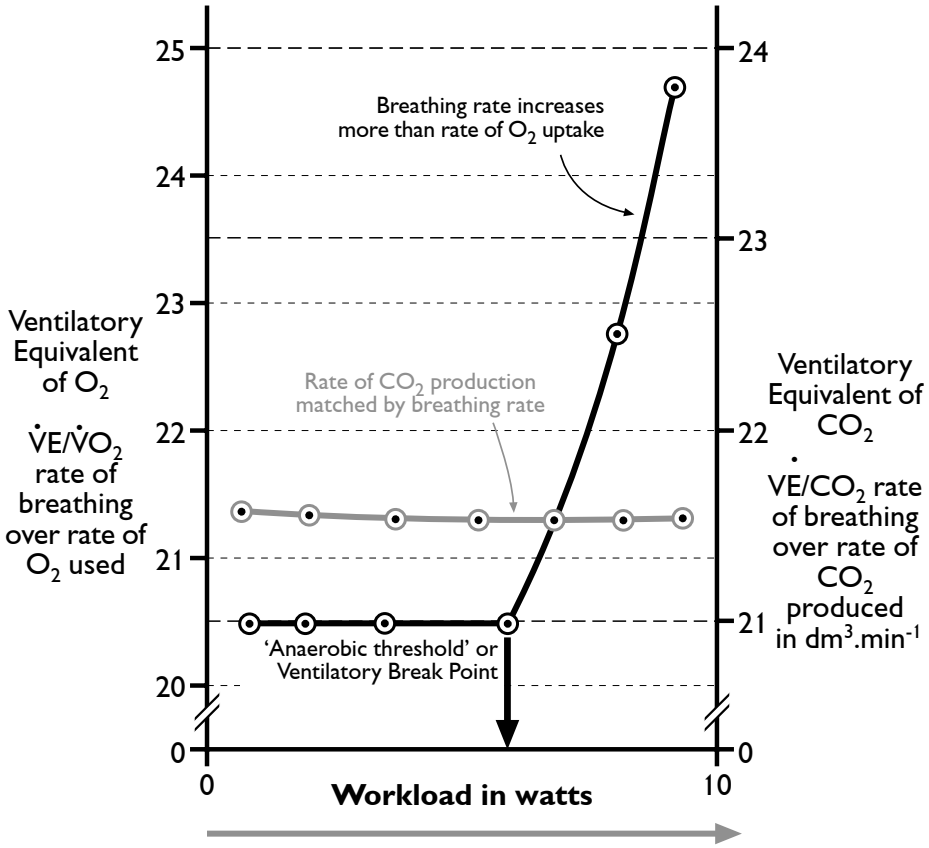
In order to achieve the same heart rate *(from a lower starting resting heart rate)* during the post training exercise period, the intensity of exercise was higher than before.

These heart rate trends mirror those of the cardiac output and oxygen uptake, as the heart rate reflects the oxygen demands of the body, both during exercise and after *(excess post-exercise oxygen consumption or EPOC)*.

The greater work load to achieve the same heart rate, and the quicker recovery pattern in the heart rate after training reflects the greater aerobic efficiency after training.

The ventilatory *(breathing)* 'break' point or 'anaerobic threshold'

Graph 14



These curves reflect the fact that CO_2 production and an associated drop in blood pH *(increase in acidity)* are the main stimuli to increase the ventilation rate.

The ventilatory *(breathing)* 'break' point is that point during progressively intense aerobic effort at which the rate of breathing *(ventilation)* increases without a corresponding increase in oxygen uptake, ie the rate of breathing has 'broken' away from the uptake of extra oxygen.

The aerobic oxidation of simple carbohydrates *(eg glucose)* produces a volume of carbon dioxide which is equal to the volume of oxygen consumed:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$$

The oxidation of fatty acids is always aerobic, and more oxygen is consumed than carbon dioxide produced.

So with a combination of the aerobic respiration of carbohydrates and fats there is a net greater consumption of oxygen than production of carbon dioxide.

Continued.....

Anaerobic processes increase the production of carbon dioxide without a linear increase in the uptake of oxygen. In anaerobic respiration carbohydrates are converted to lactic acid:

$$C_6H_{12}O_6 \rightarrow \text{Lactic acid}$$

At the pH levels of the body fluids lactic acid dissociates almost completely into lactate ions and hydrogen ions:

$$\text{Lactic acid} \rightarrow \text{Lactate} + H^+$$

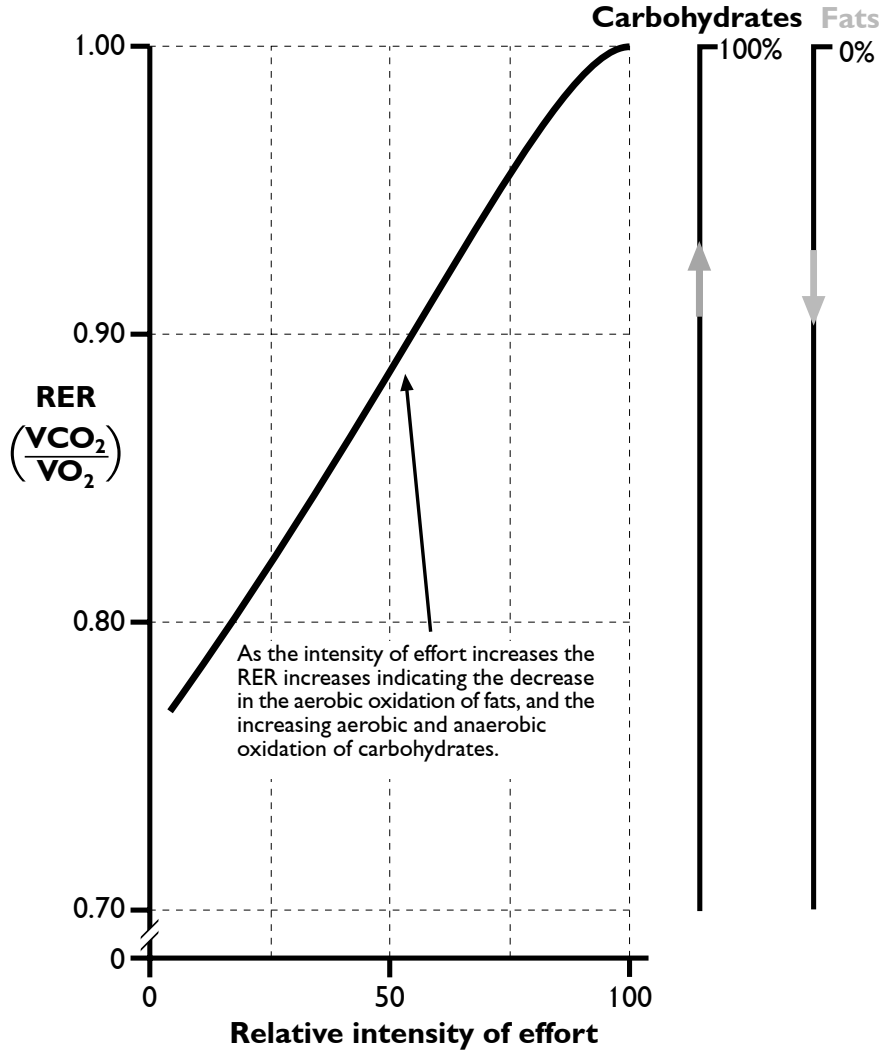
These interact with sodium hydrogen carbonate in the plasma to form sodium lactate, water, and carbon dioxide.

$$\text{Lactate} + H^+ + \text{Sodium hydrogen carbonate} \rightarrow \text{Sodium lactate} + H_2O + CO_2$$

Therefore, the more anaerobic respiration there is the more carbon dioxide is released than oxygen consumed. The hydrogen ions and the carbon dioxide stimulate an increase in the rate of ventilation *(breathing)* which serves to eliminate the excess carbon dioxide, but does not result in an increase of oxygen uptake.

Estimation of the respiratory substrates and the type of respiration from the Respiratory Exchange Ratio *(RER)* in relation to intensity of effort

Graph 15



The respiratory substrates are carbohydrates *(glycogen/glucose)*, fats *(fatty acids and glycerol)*, and protein *(amino acids)*. Their oxidation to release energy, some of which is trapped in ATP, consumes different amounts of oxygen and produces different amounts of carbon dioxide.

The aerobic oxidation of simple carbohydrates *(eg glucose)* produces a volume of carbon dioxide which is equal to the volume of oxygen consumed:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$$

Continued.....

Therefore the ratio of the volume of carbon dioxide produced over the volume of oxygen consumed *(or RER)* is unity i.e. one:

$$6CO_2 / 6O_2 = 1$$

As the biochemical events of respiration cannot be observed directly a RER of one can be taken as an indication that carbohydrates are being respired aerobically.

However, the situation is different in the more complex equations of the aerobic oxidation of fats *(fatty acids and glycerol)* and protein *(amino acids)*.

The RER for the oxidation of fats being about 0.7, and the RER for the aerobic oxidation of proteins being about 0.8. In other words these reactions consume more oxygen than they produce carbon dioxide.

The involvement of anaerobic respiration further complicates the picture as there is a decline, and subsequent levelling off of O_2 uptake with increasing work load, whereas CO_2 production increases above the rate comensurate with the rate of aerobic respiration. This means that the RER will increase the more anaerobic respiration is involved.

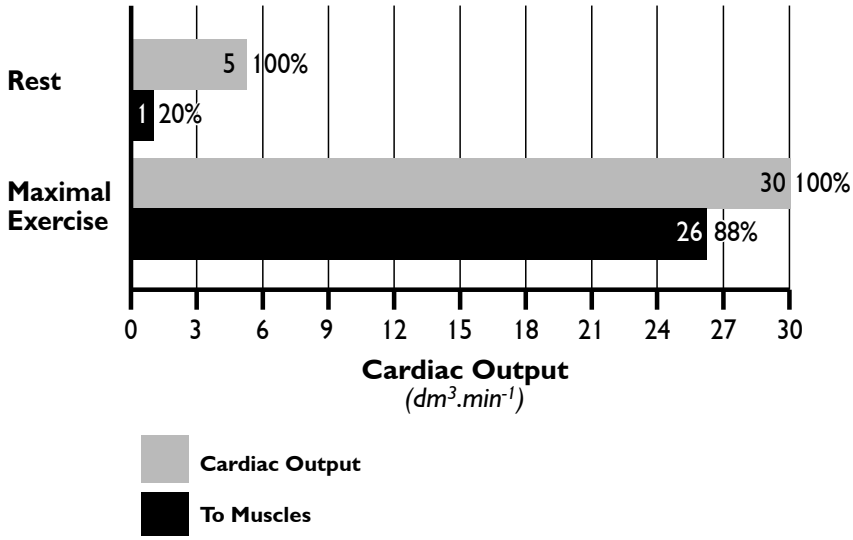
As all types of substrate, and both aerobic and anaerobic respiration, are always involved, the resulting RER will be a complex combination of these process, and no firm conclusions can be drawn from it. However, it does provide some insight into the respiratory processes that are going on at any time.

Estimated blood flow in cm^3 per minute to different organ/systems in a trained male at rest and during maximum effort

Graph 16

Organ System	At Rest	%	Max Effort*	%
Skeletal muscle	1000	20	26000	88.00
Coronary vessels	250	5	1200	4.00
Skin	500	10	750	2.50
Kidneys	1000	20	300	1.00
Liver & gut	1250	25	375	1.25
Brain	750	15	750	2.50
Whole body	5000	100	30000	100.00

*Cycle Ergometer



The shunting of blood to the active muscles is but an extreme example of that which is going on continuously at all times, as the body adapts to continually changing activity and circumstances.

The figures given are approximations, and depend on many circumstances, eg external temperature, time of the last meal, and the condition of the subject.

The percentage supplied to the coronary vessels remains of the same order, and this reflects the fact that the heart must do proportionally the same amount of work pumping a larger amount of blood as pumping a lesser amount.

The figures for the flow to the skin can vary widely depending on conditions, and state of hydration of the athlete. The flow to the skin will increase, in order to dissipate the excess heat produced during exercise, by conduction, convection, and radiation.

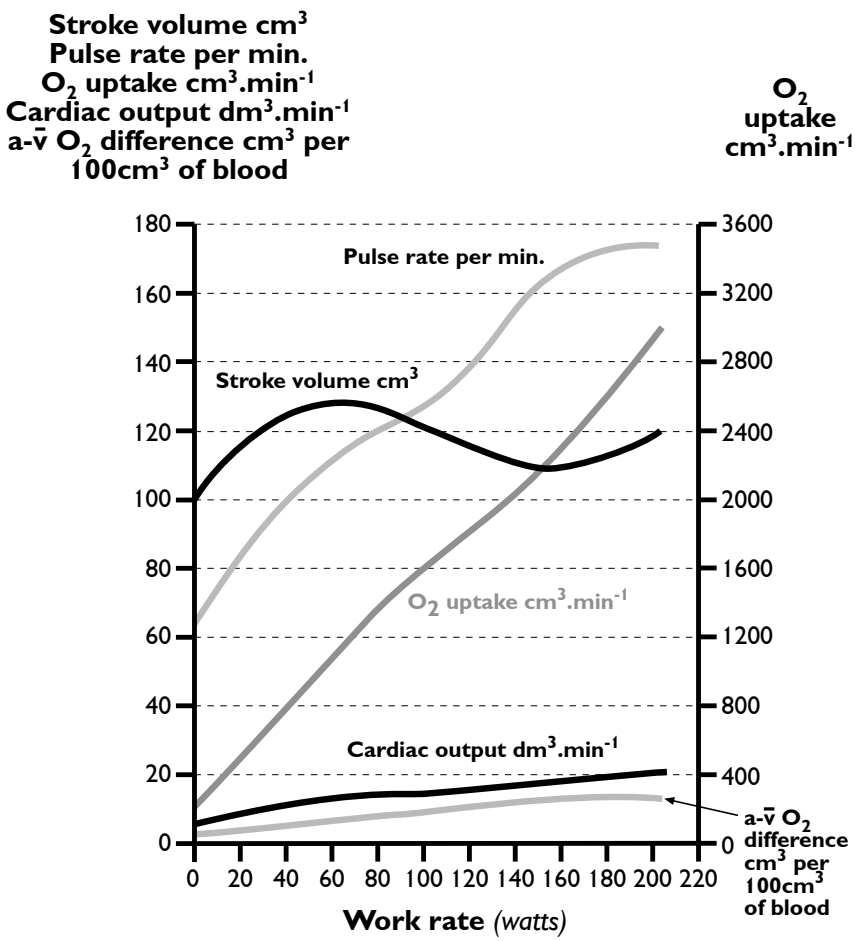
Continued.....

The kidneys and the liver are not harmed by such dramatic reductions in their blood flow, as the large volumes of blood supplied to them at rest are to enable them to carry out their blood homeostasis functions, eg excretion and maintenance of blood glucose levels. The reduced blood flow during exercise is still sufficient to supply the needs of their tissues.

Some authorities will show a reduction in the blood flow to the brain during exercise, but reasoning at least would favour the maintenance of a constant blood flow to the brain, as there is no significant change in its function during exercise, and its blood supply must always be at an optimum to ensure correct functioning.

Response of some physiological measures to increasing sub-maximal work rates

Graph 17



These curves are based on actual data measured on a subject undergoing a laboratory test, and therefore show variations away from the expected ideal. They are included as a reminder that actual measurements do show a range of variation, and that such variations should be accepted as such, and not be 'tidied up'. This should give candidates a much more realistic view of the nature of testing, and be better prepared for any such variations that occur in their tests.

a-v̄O_2 difference is the difference between the oxygen concentrations in the mixed venous blood returning to the lungs in the main veins and the arterial blood that has been oxygenated in the lungs. The lower the concentration of oxygen in the mixed venous blood *(that is venous blood from the active muscles and other tissues of the body not directly involved in exercise)* returning to the lungs, the greater the diffusion gradient between the deoxygenated blood in the capillaries of the pulmonary

Continued.....

circulation and the air in the alveoli of the lungs, and the greater the oxygen uptake. It increases proportionally to work rate, as the working muscles extract more and more oxygen from the blood.

Cardiac output in this sub-maximal test also increases proportionally with work rate as the working muscles demand more and more oxygen.

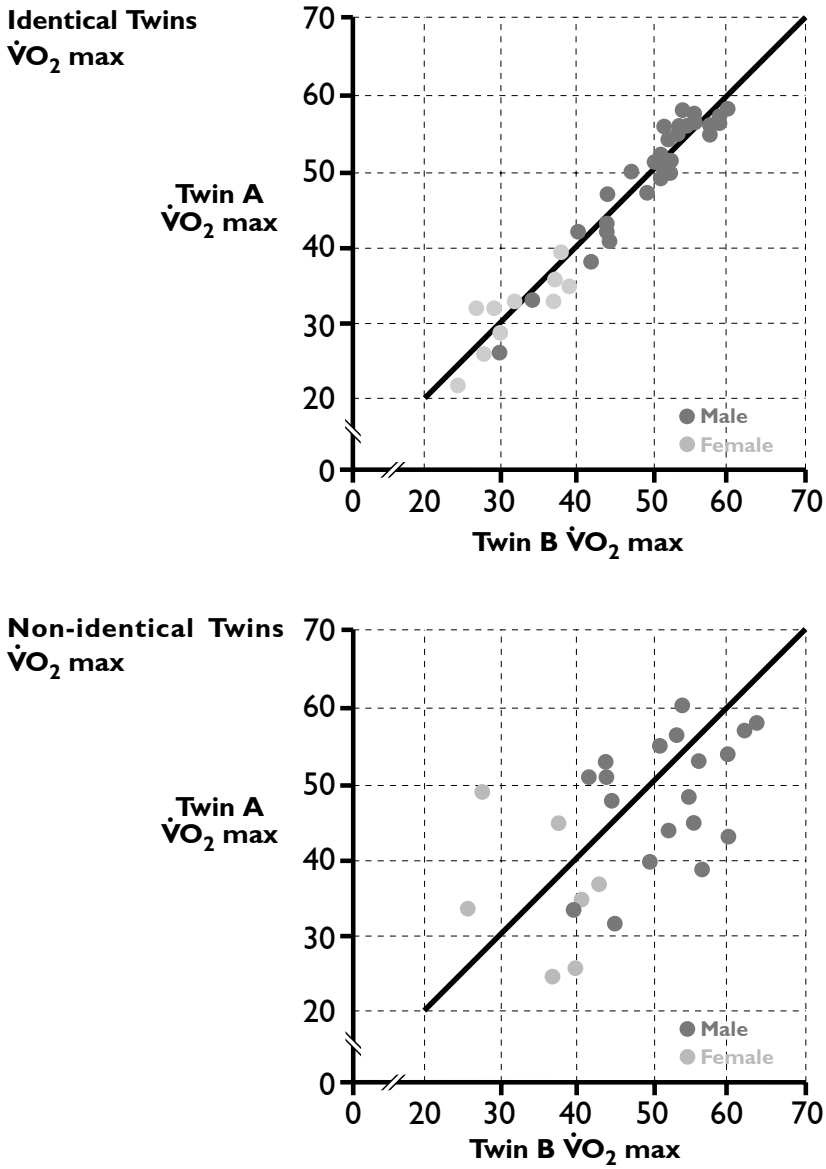
Pulse rate in this sub-maximal test also increases proportionally with work rate as the working muscles demand more and more oxygen. The fluctuations away from the straight line relationship are normal variations within acceptable limits.

Oxygen uptake in this sub-maximal test also increases proportionally with work rate as the working muscles demand more and more oxygen.

Stroke volume levels off as the pulse rate increases, as the ventricles cannot fill completely in the shorter filling period *(ventricular diastole)* between beats. The variation away from the ideal shape of the curve, as with all the curves, is a result of all these curves being based on actual data measured on a subject undergoing a laboratory test.

Correlations of VO_2max between members of pairs of twins

Graph 18



The strong correlation between the VO_2max of members of a pair of identical twins results in the points of the graph clustering around the straight line which represents perfect correlation. Whereas, it is clear to see on the graph of non identical twins that there is virtually no correlation of VO_2max between members of pairs.

These graphs provide a very clear illustration of the importance of inherited capacities in sport performance. These considerations are of the utmost importance for an intelligent approach to training and coaching programmes.

Continued.....

It is also an area where, despite protestations of some that they are self made, the commonsense observation that 'champions are born and not made' prevails. Remembering of course that these two components are so integrated that they can never be dealt with in isolation.

GENOTYPE + ENVIRONMENT = PHENOTYPE

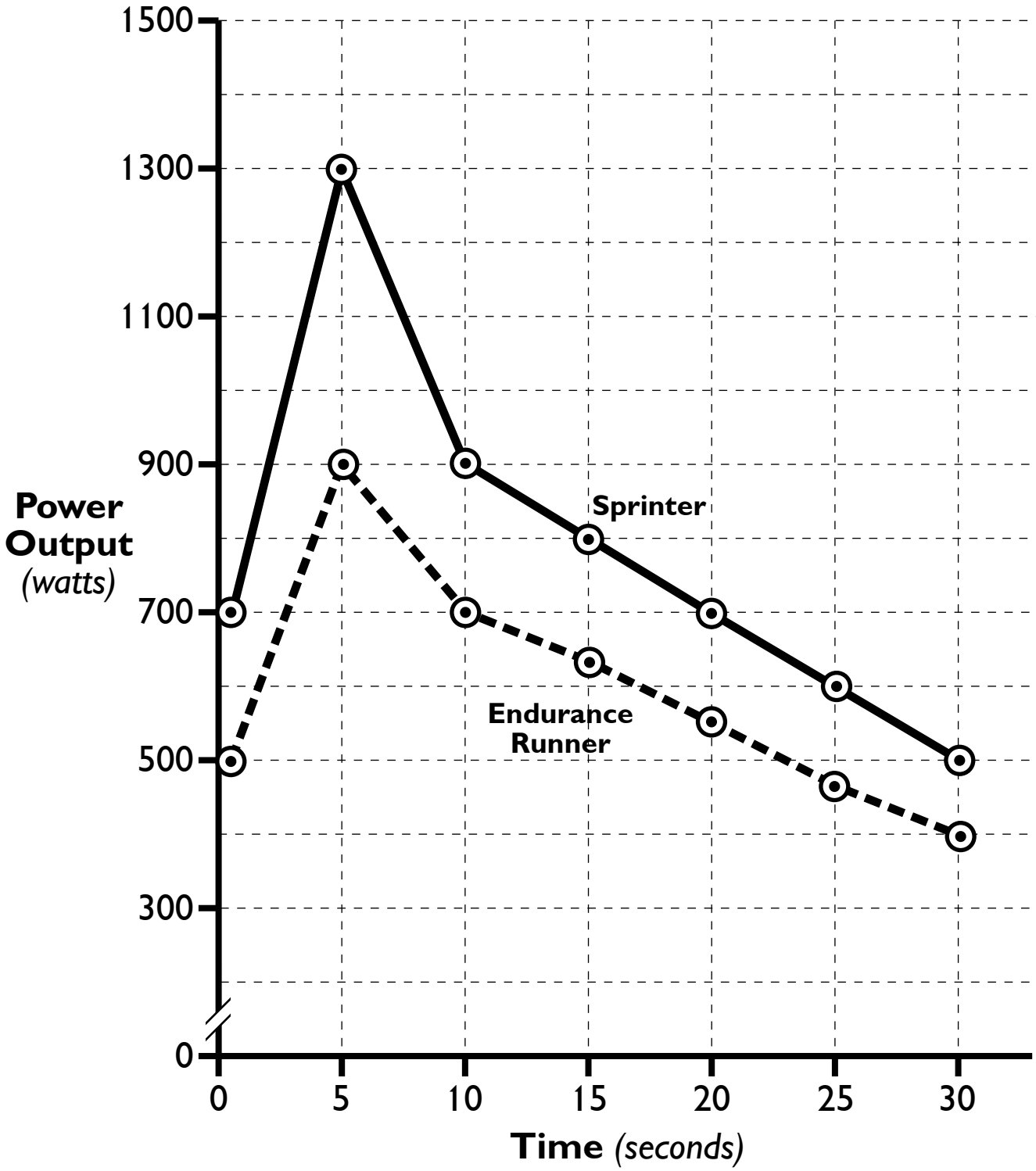
Where the genotype is the genetic make up an organism, and the phenotype is the end result of that genotype interacting with the environment.

APPENDIX

A4 Black & White Versions 1- 18

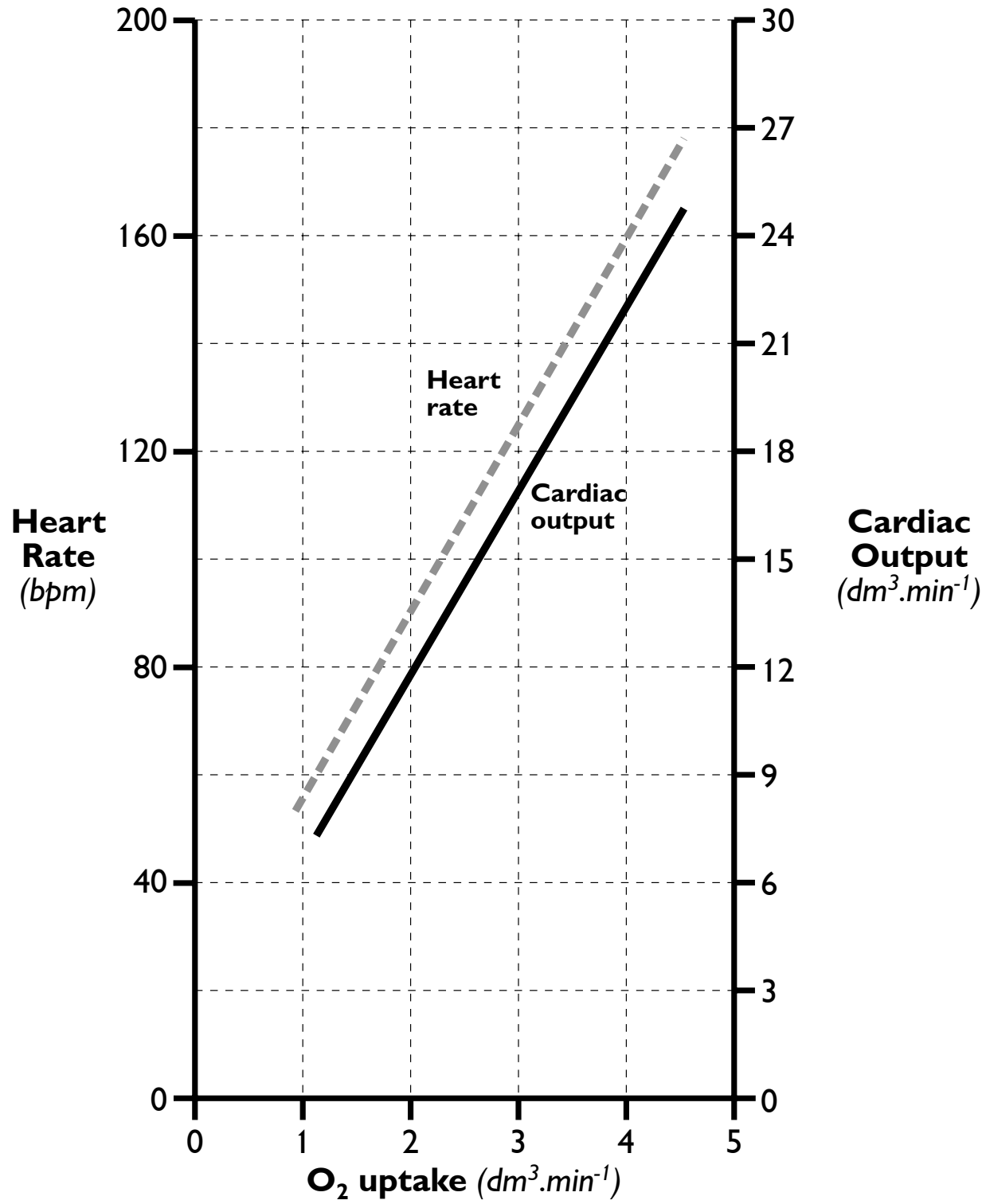
Power output of a sprinter and an endurance runner in a Wingate test on a cycle ergometer

1

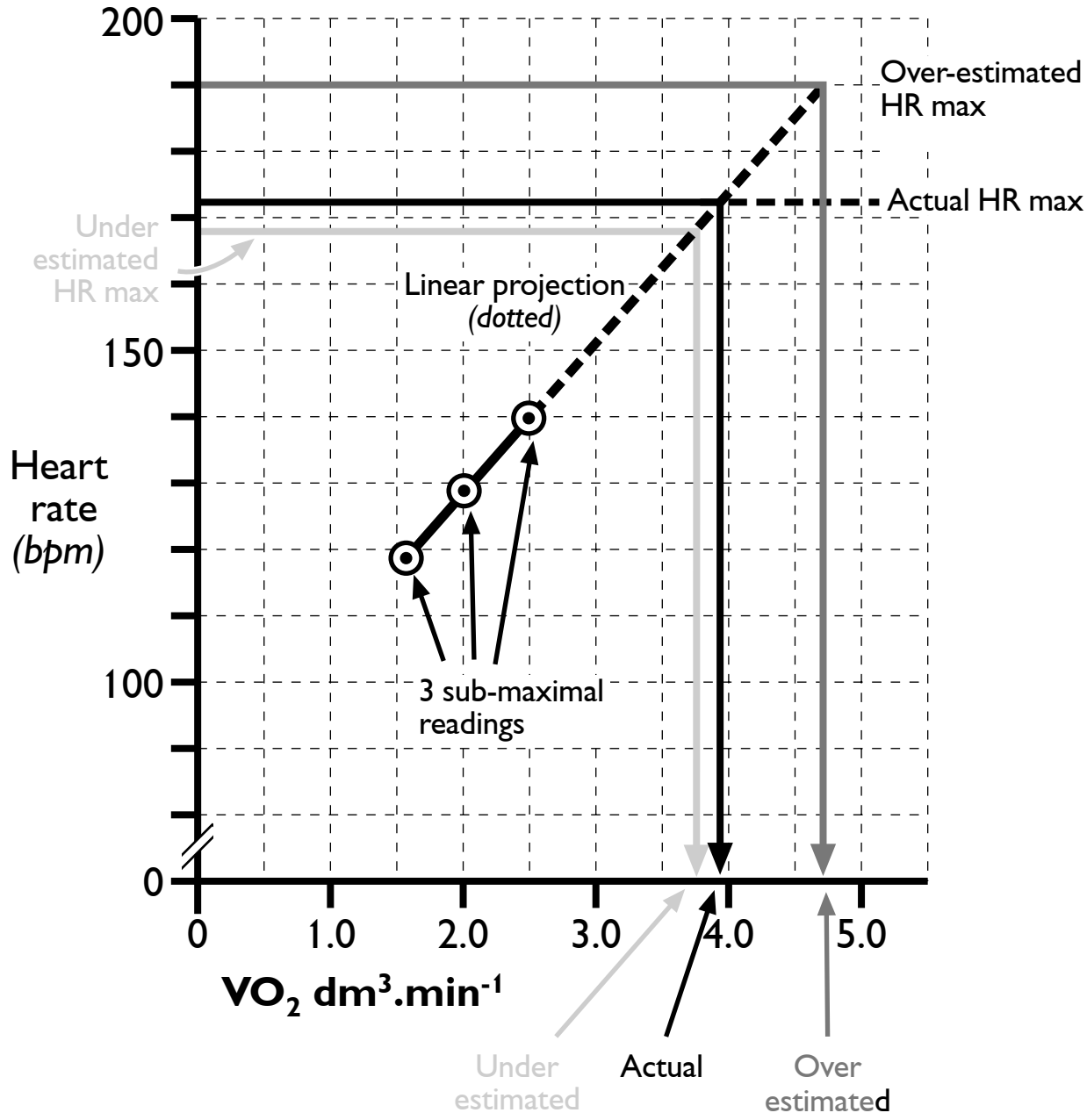


Ideal linear relationship between heart rate and oxygen uptake, and cardiac output and oxygen uptake, at sub-maximal work rates

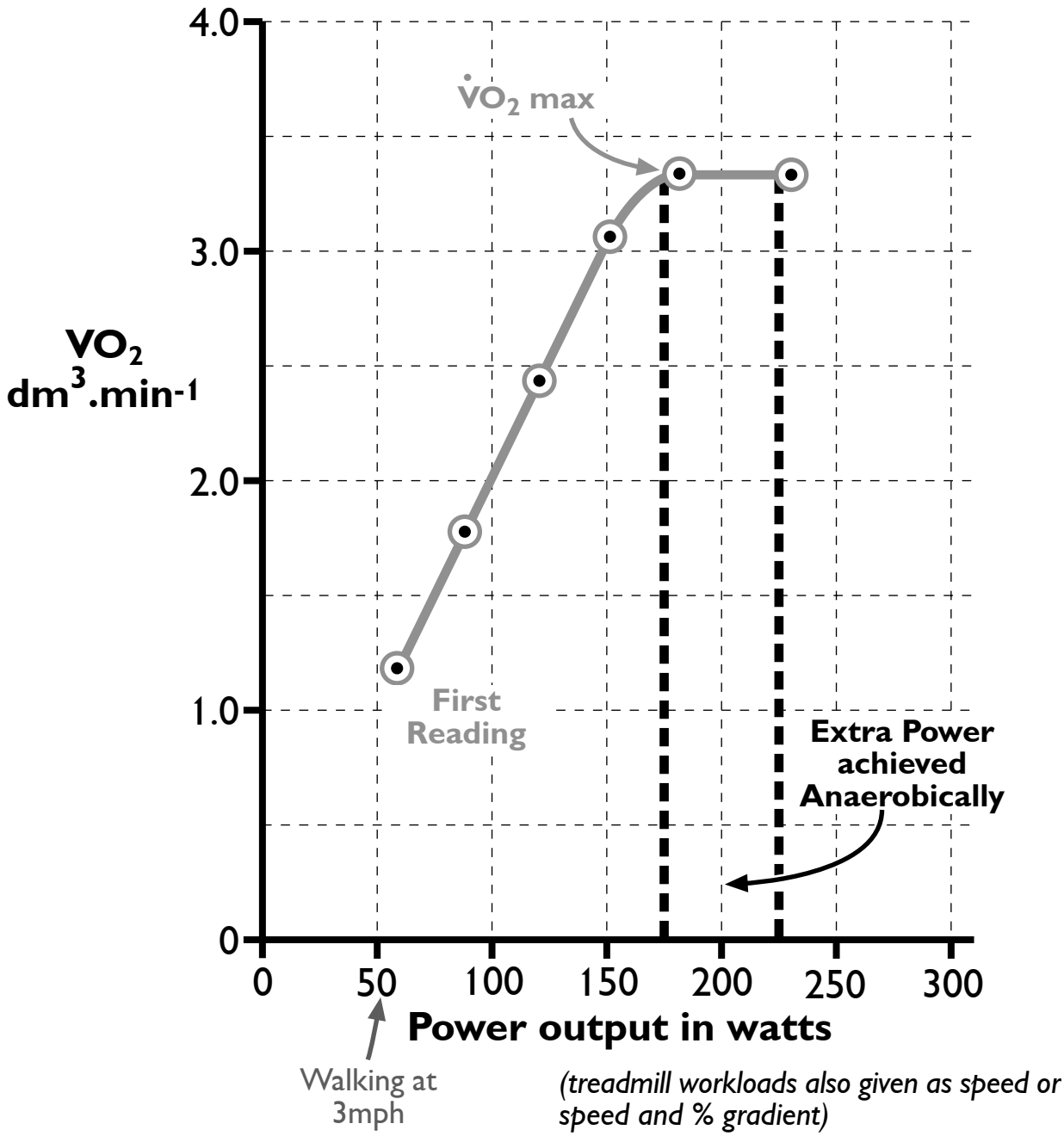
2



Projection of maximum oxygen uptake from heart rates in a progressive incremental sub-maximal test

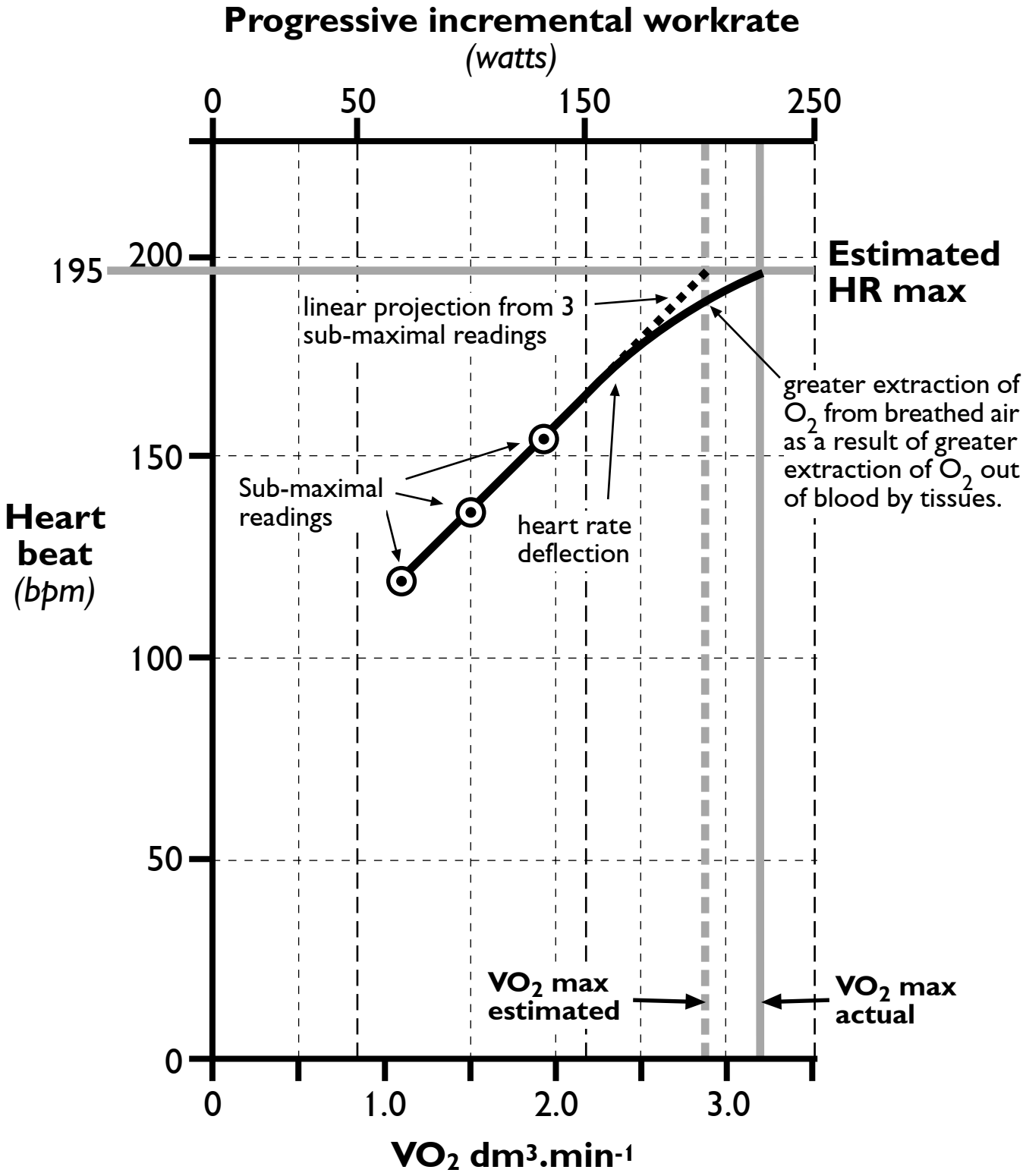


Oxygen uptake in relation to work output in a progressive maximal test

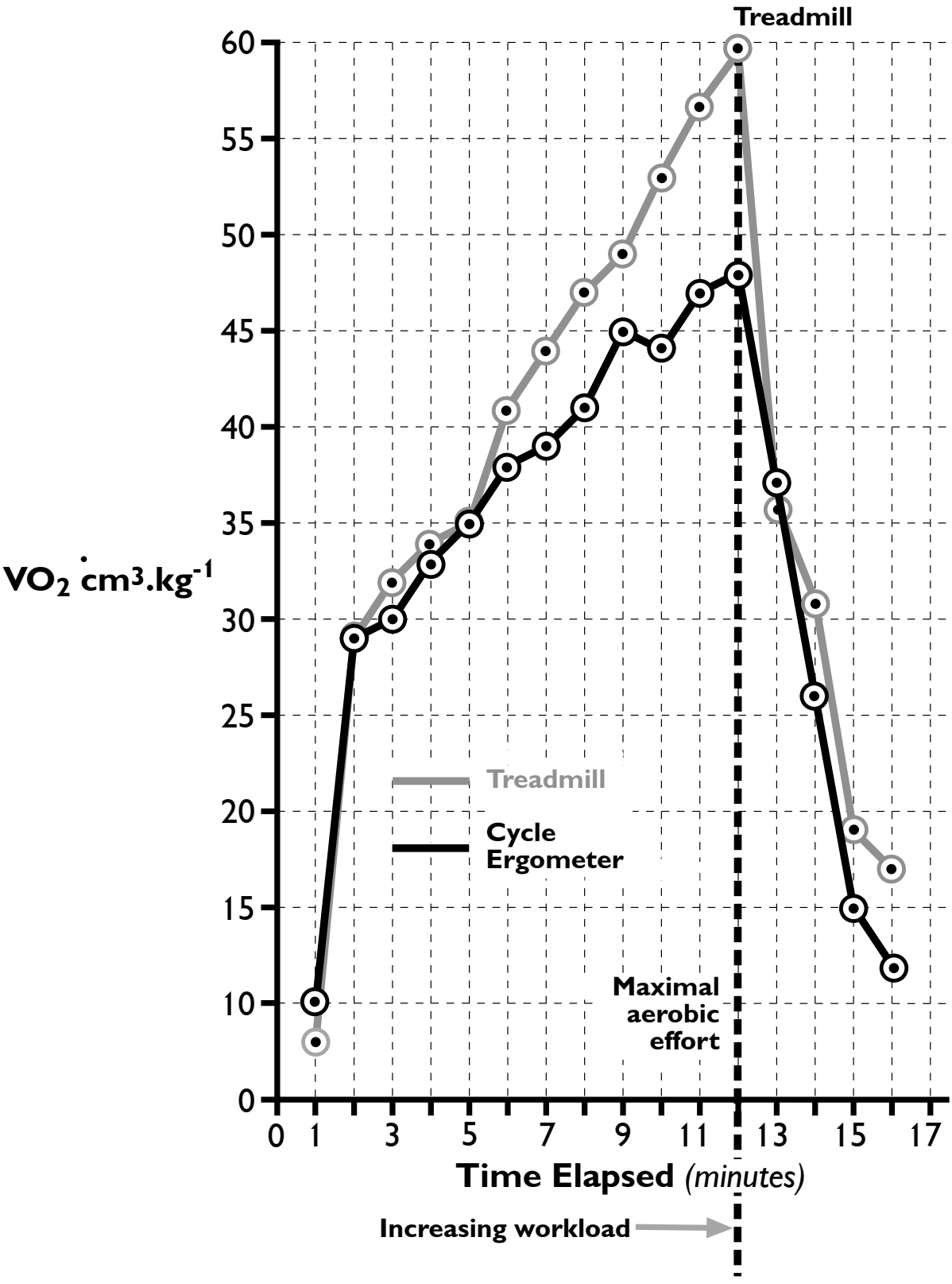


2 minutes at 60 watts and then increments of 30 watts every 2 minutes.
A watt is the unit of rate of work or power $1w = 1J.s^{-1}$.
A reasonably fit person could maintain about 200 watts for an hour.
Tour de France riders maintain about 250 watts for seven hours.
Peak power outputs are as high as 1500 watts.

The relationship between heart rate, work rate, and oxygen uptake during progressive incremental maximal testing

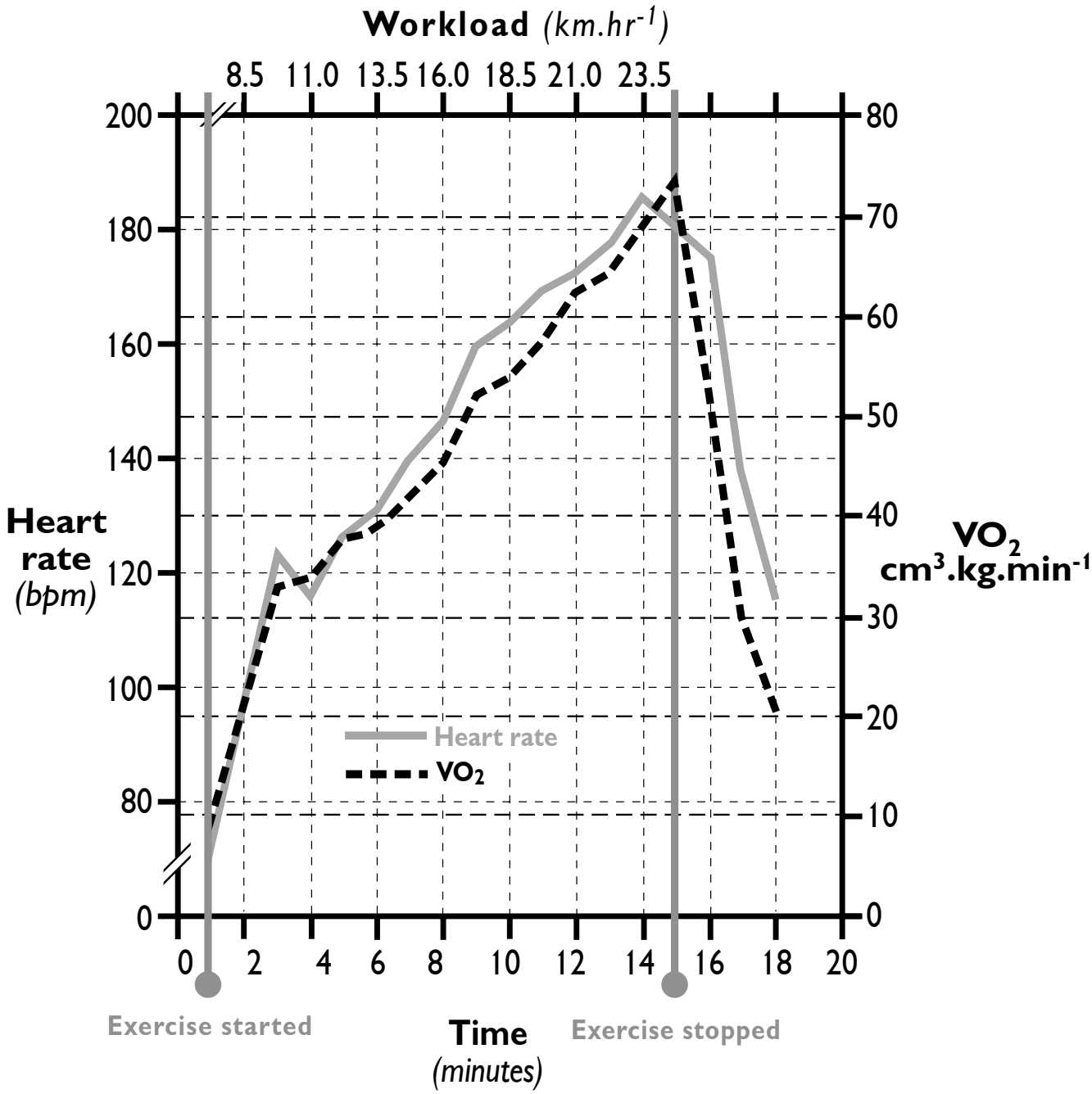


Oxygen uptake against time in a single subject during a progressive maximal test on *(i)* a treadmill; and *(ii)* a cycle ergometer.



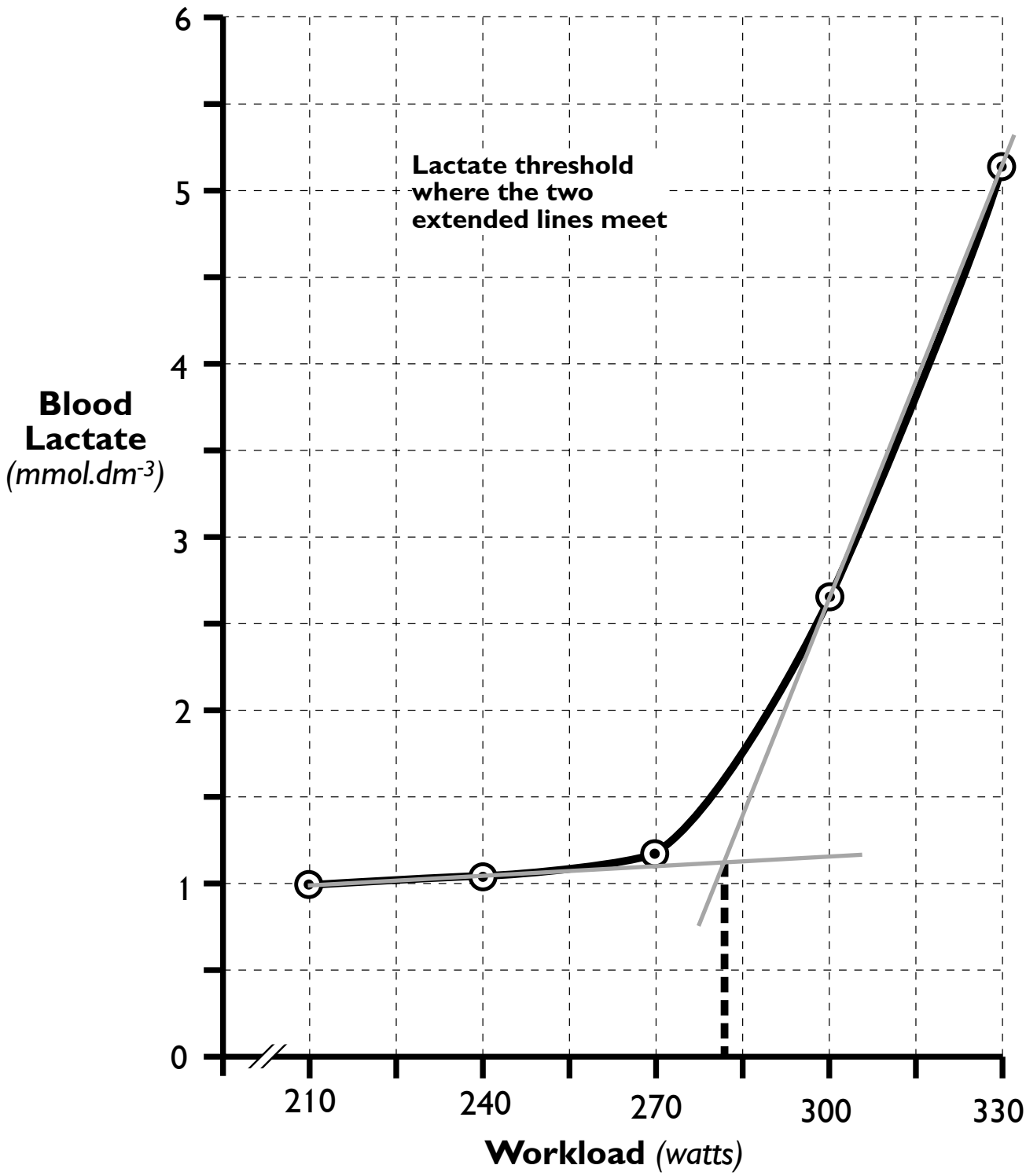
Heart rate and oxygen uptake against time of a middle distance runner during a progressive maximal treadmill test

7

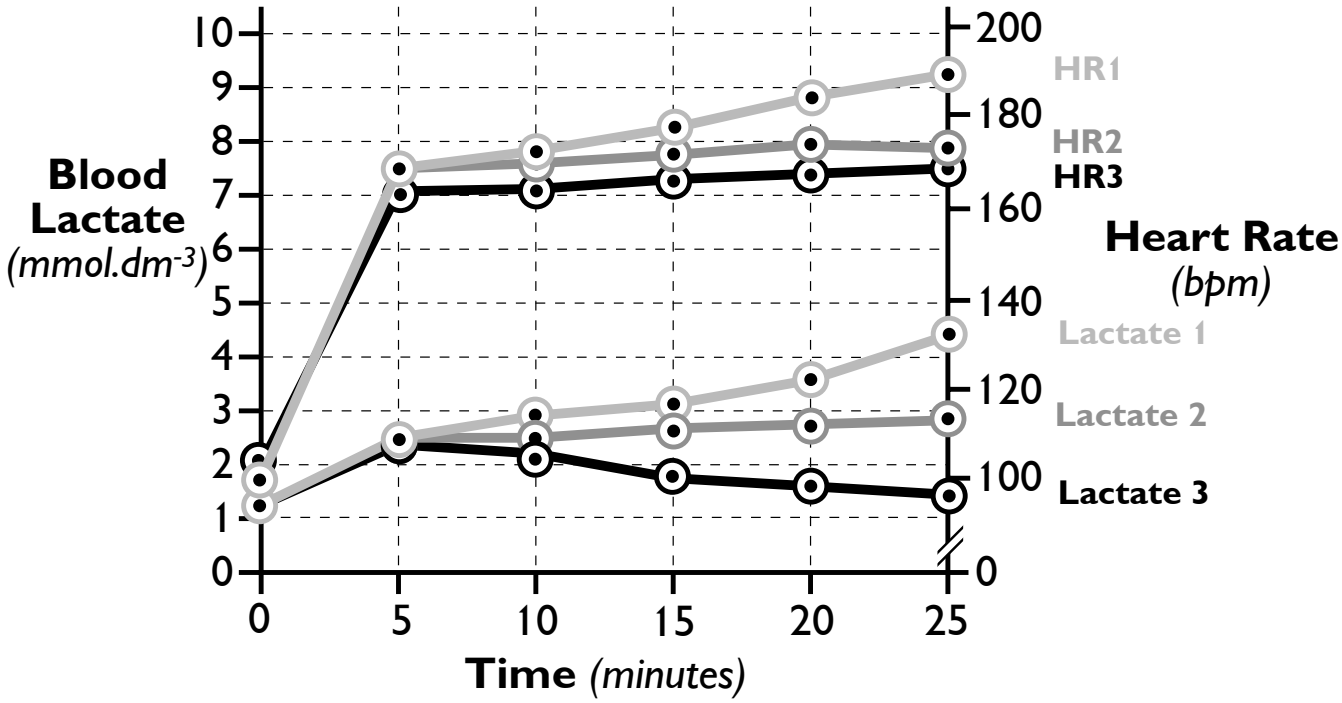


Determination of Lactate Threshold in a progressive incremental test by projection

8

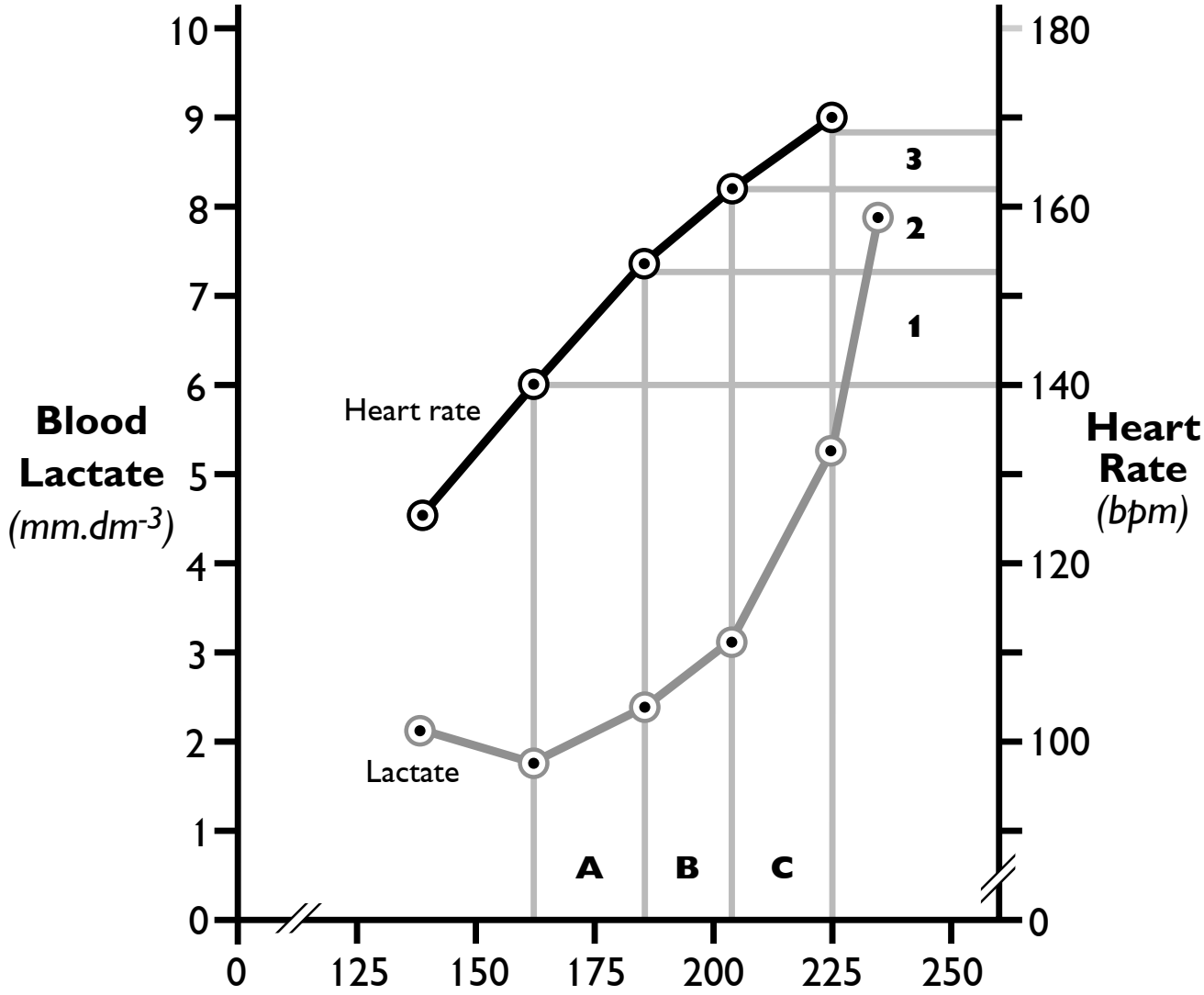


Determination of Maximum Lactate Steady State in a progressive incremental test



Progressive Incremental Work Load	Time in minutes	0.0	5.0	10.0	15.0	20.0	25.0
Load 1	Lactate 1	1.31	2.49	2.50	2.67	2.72	2.80
	HR 1	100	169	171	173	174	173
Load 2	Lactate 2	1.31	2.50	2.90	3.10	3.54	4.36
	HR 2	104	170	173	178	185	190
Load 3	Lactate 3	1.31	2.40	2.22	1.80	1.60	1.40
	HR 3	104	166	165	167	168	169

Determination of heart rate training zones from blood lactate measurements during progressive incremental work loads



Power Output *(watts)*
during progressive incremental test

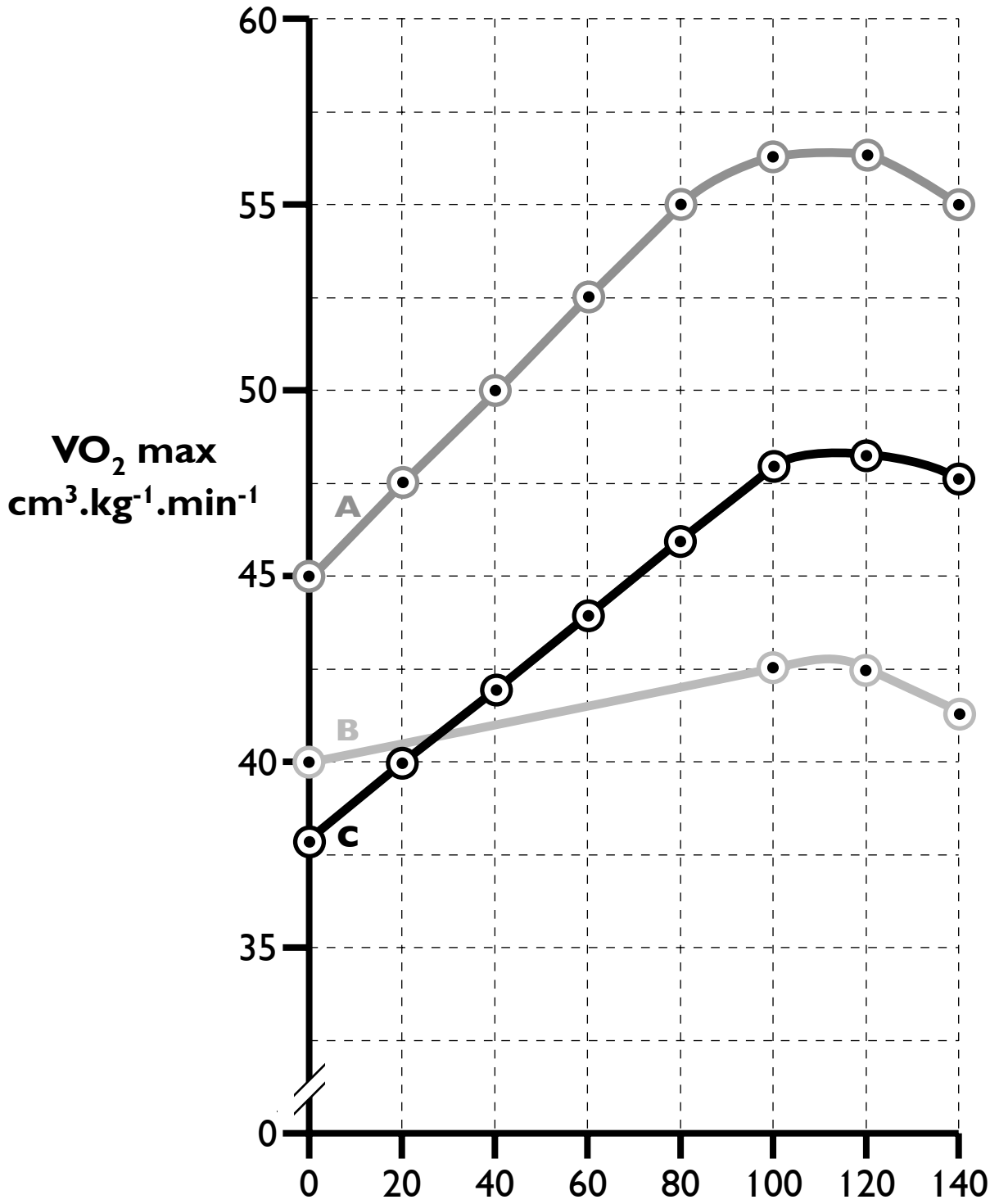
4 minute efforts at each work load
Lactate sampled
30 seconds rest
4 minutes at next work load

A - base endurance steady state
B - upper endurance steady state
C - anaerobic threshold zone

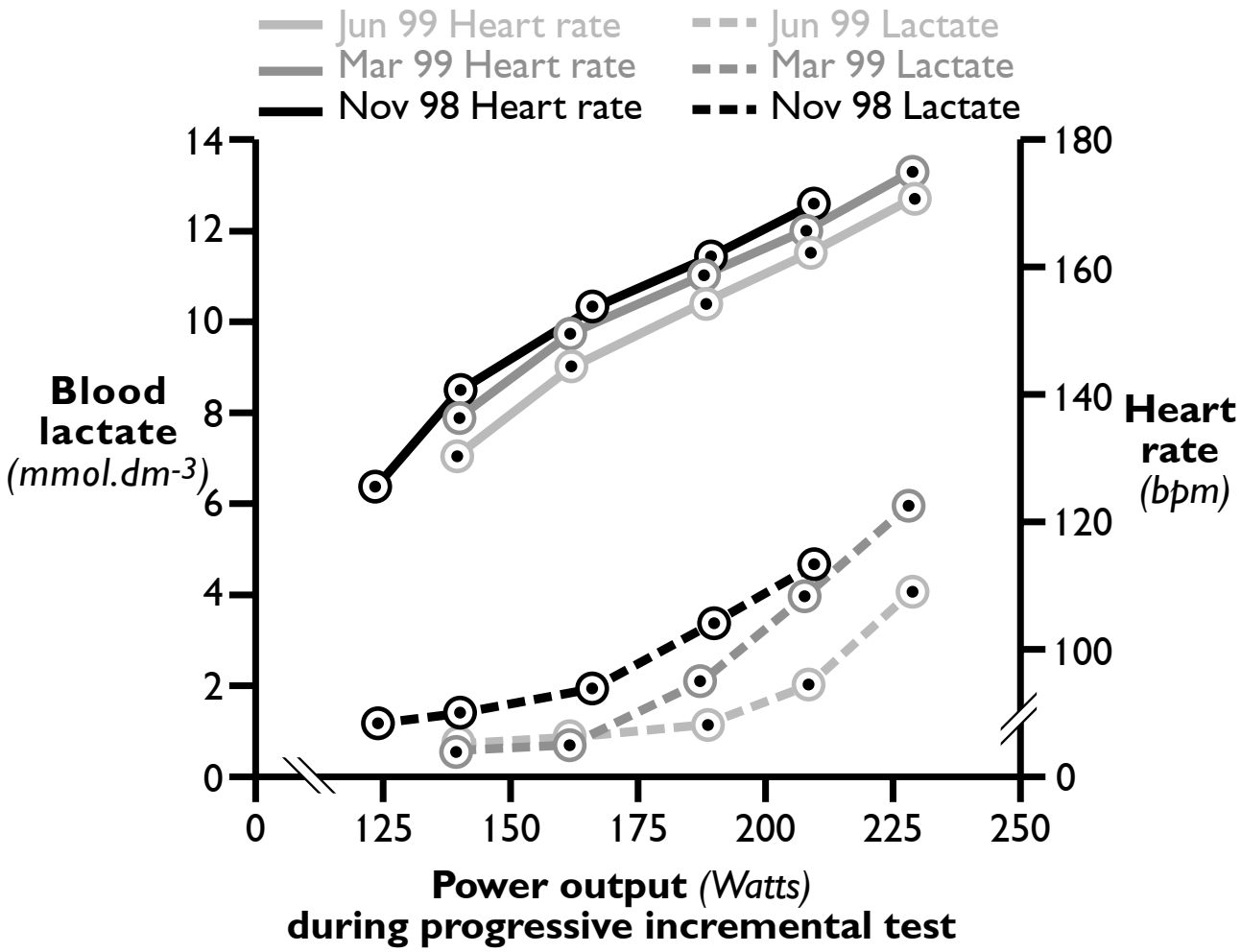
1, **2**, **3** } corresponding training heart rate zone

The effect of endurance training on maximal oxygen uptake

11



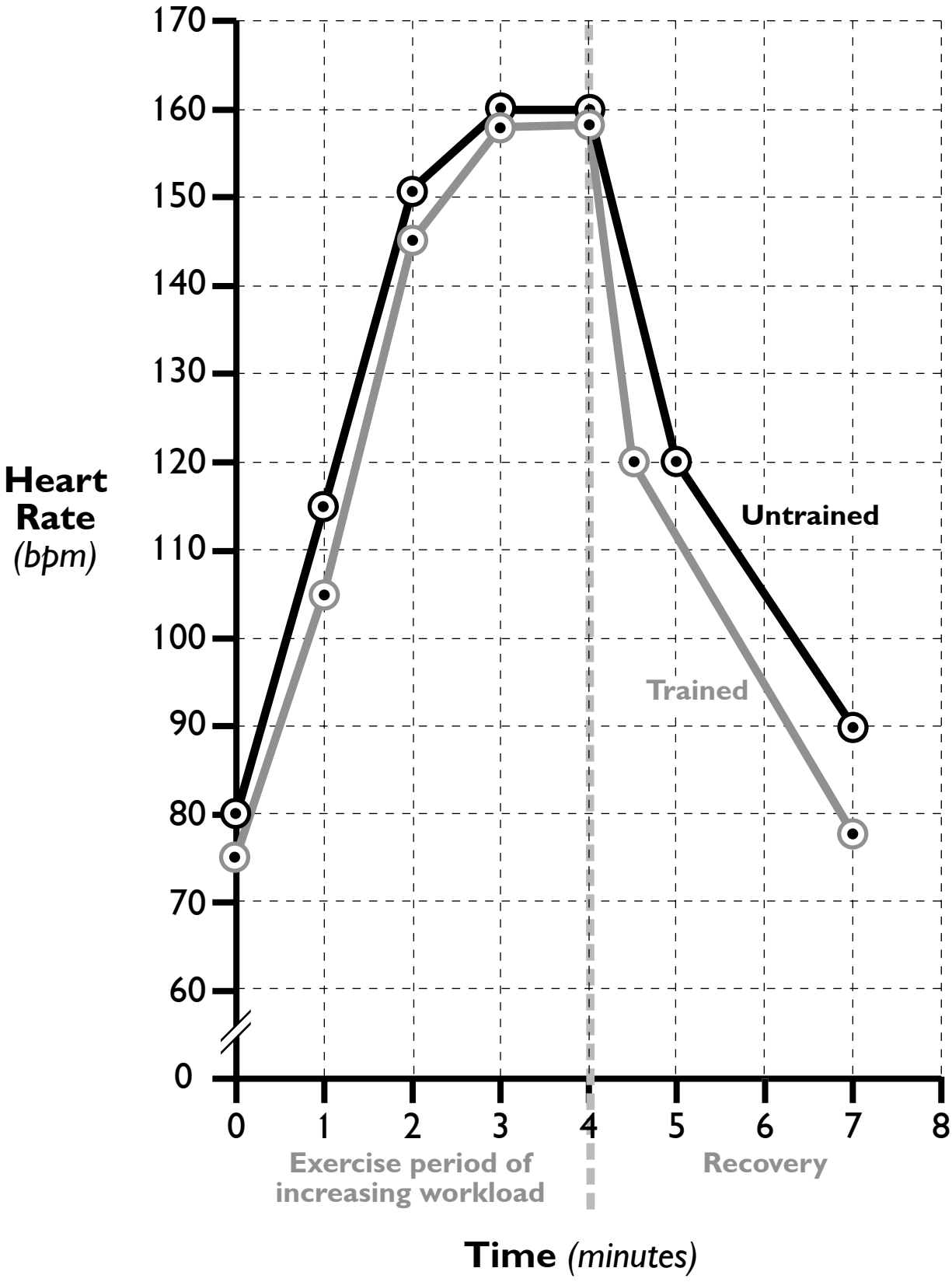
Fitness progression of an athlete as measured at 3 monthly intervals



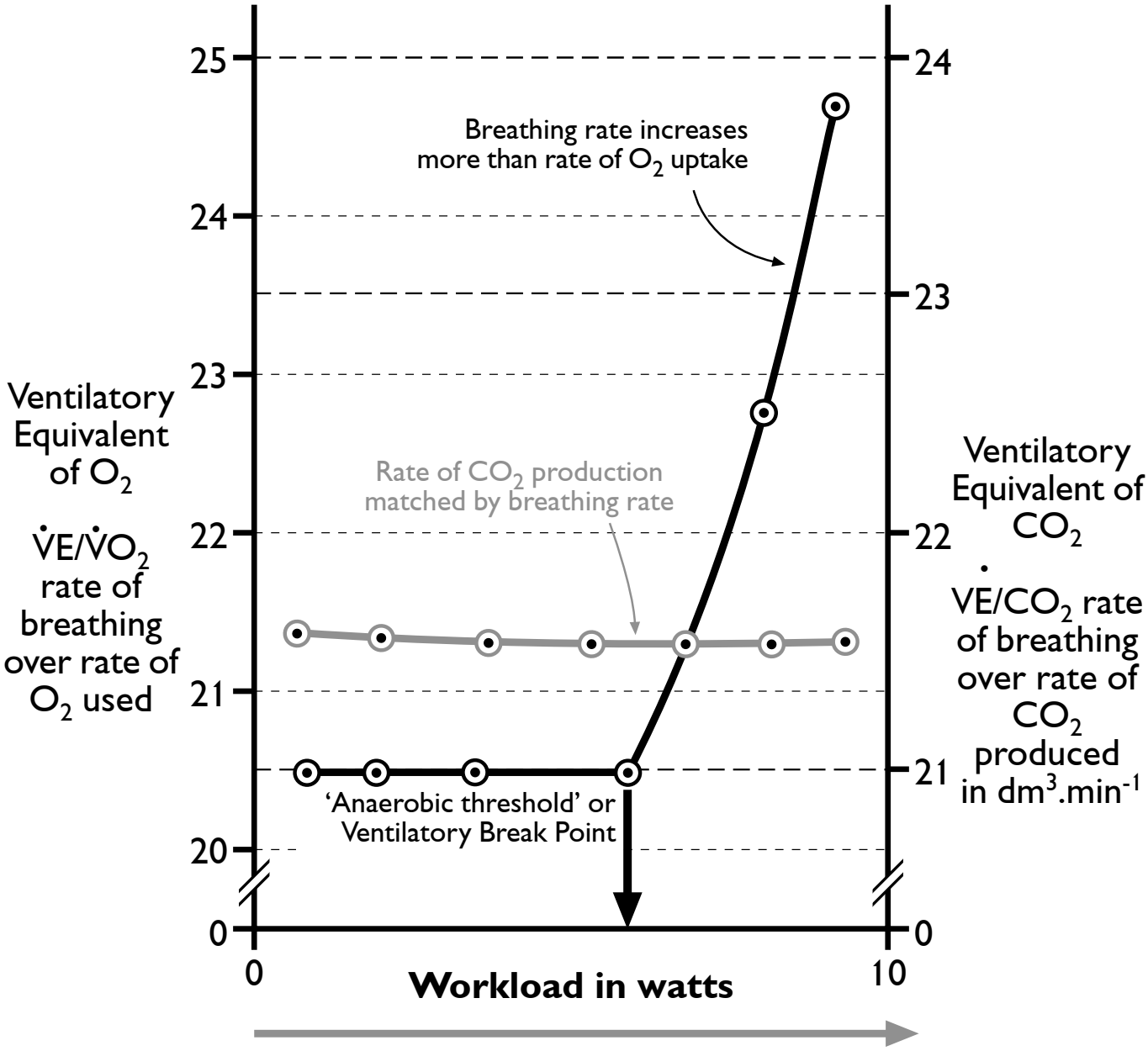
Step Test	Workload	1	2	3	4	5
Jun 99	Watts	140	162	188	208	228
	Lactate	0.70	0.90	1.20	2.06	4.09
	Heart rate	131	145	155	163	171
Mar 99	Watts	140	162	188	208	228
	Lactate	0.60	0.70	2.11	3.92	6.00
	Heart rate	137	150	159	166	175
Nov 98	Watts	124	140	166	189	209
	Lactate	1.22	1.49	2.00	3.40	4.70
	Heart rate	126	141	154	162	170

4 min efforts at each workload, lactate sampled, 30 sec rest, 4 min at next workload....

Effect of training on post-exercise recovery heart rates in a single subject

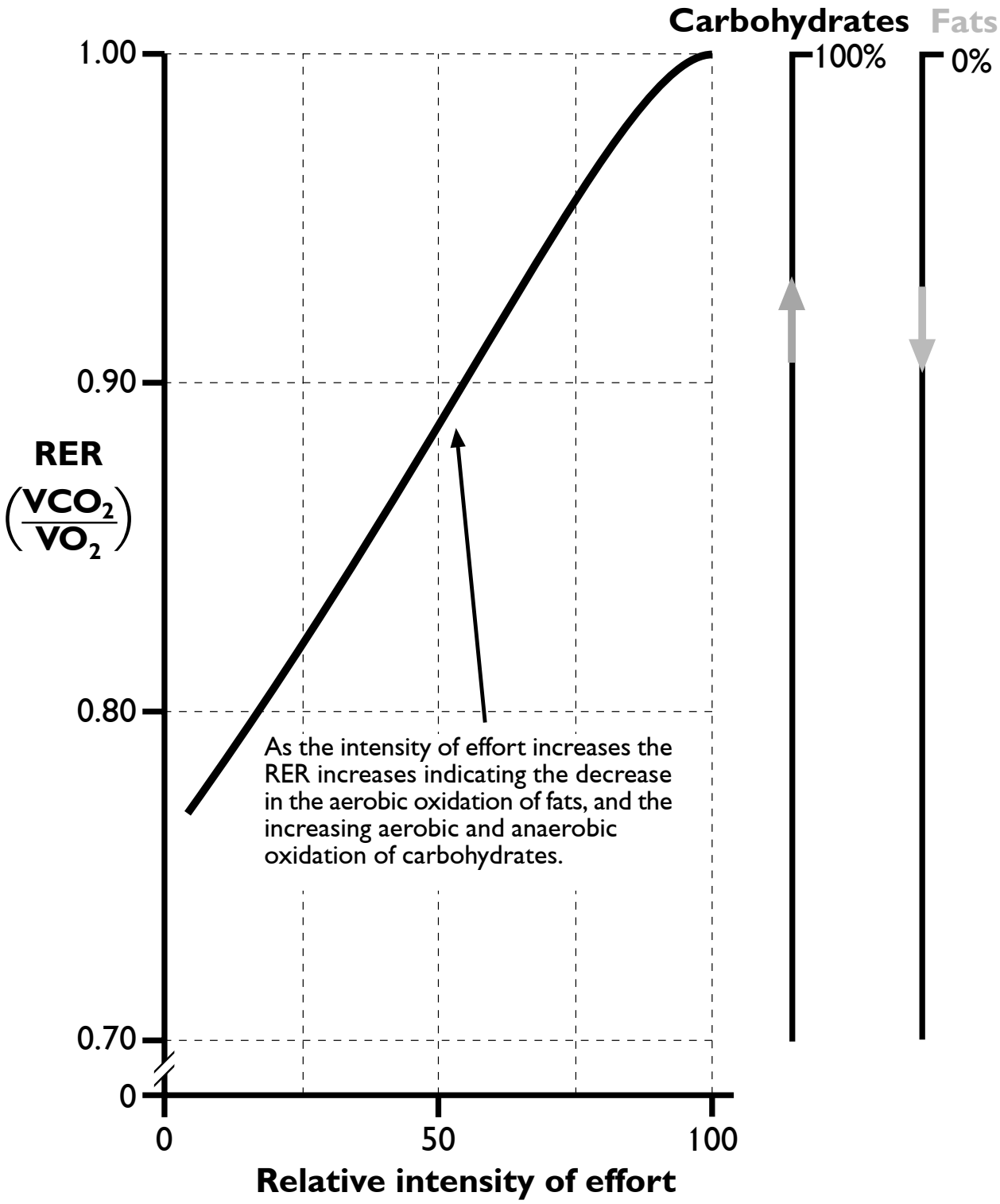


The ventilatory *(breathing)* 'break' point or 'anaerobic threshold'



These curves reflect the fact that CO_2 production and an associated drop in blood pH *(increase in acidity)* are the main stimuli to increase the ventilation rate.

Estimation of the respiratory substrates and the type of respiration from the Respiratory Exchange Ratio *(RER)* in relation to intensity of effort



Estimated blood flow in cm^3 per minute to different organ/systems in a trained male at rest and during maximum effort

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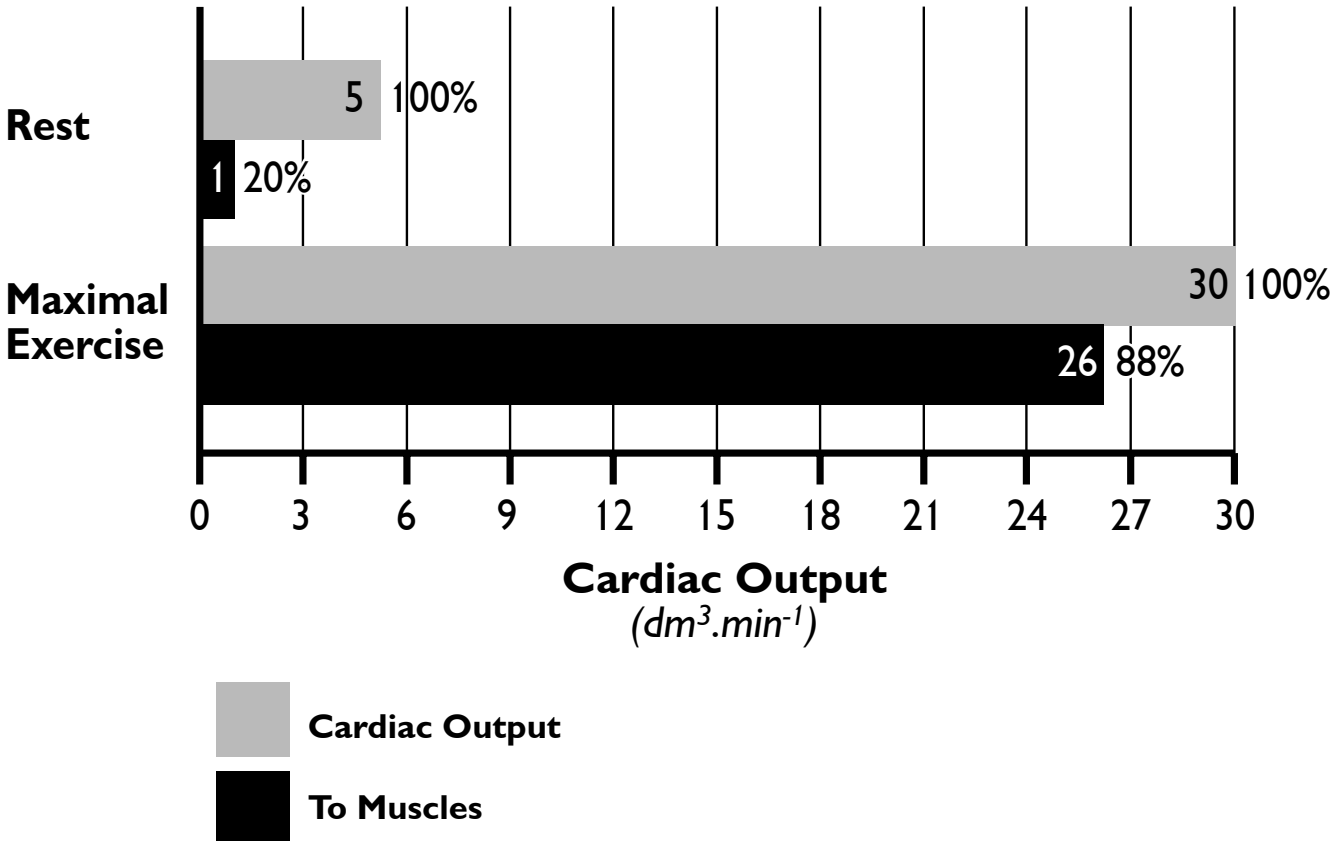
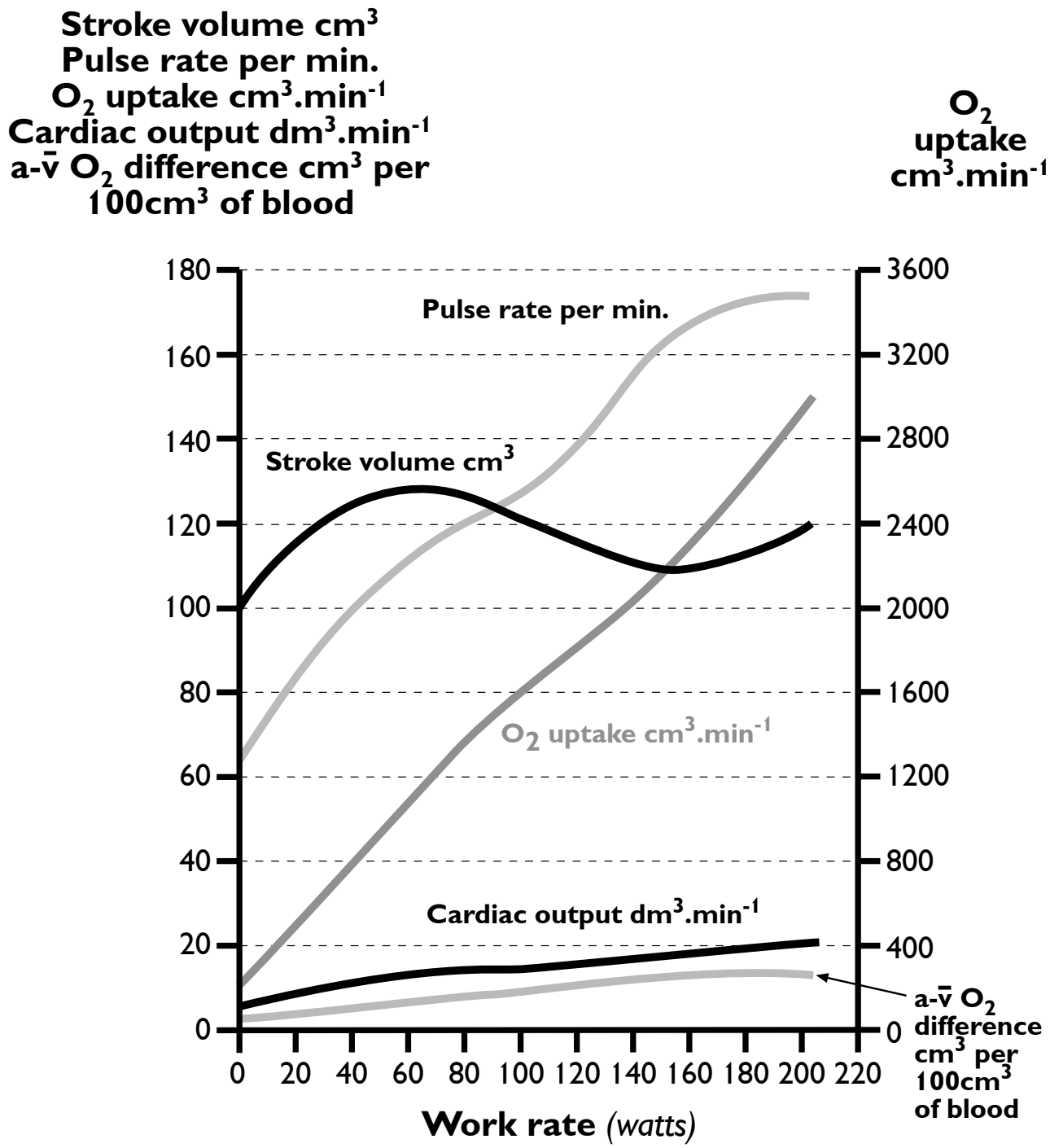
Brain	750	15	750	2.50
Whole body	5000	100	30000	100.00

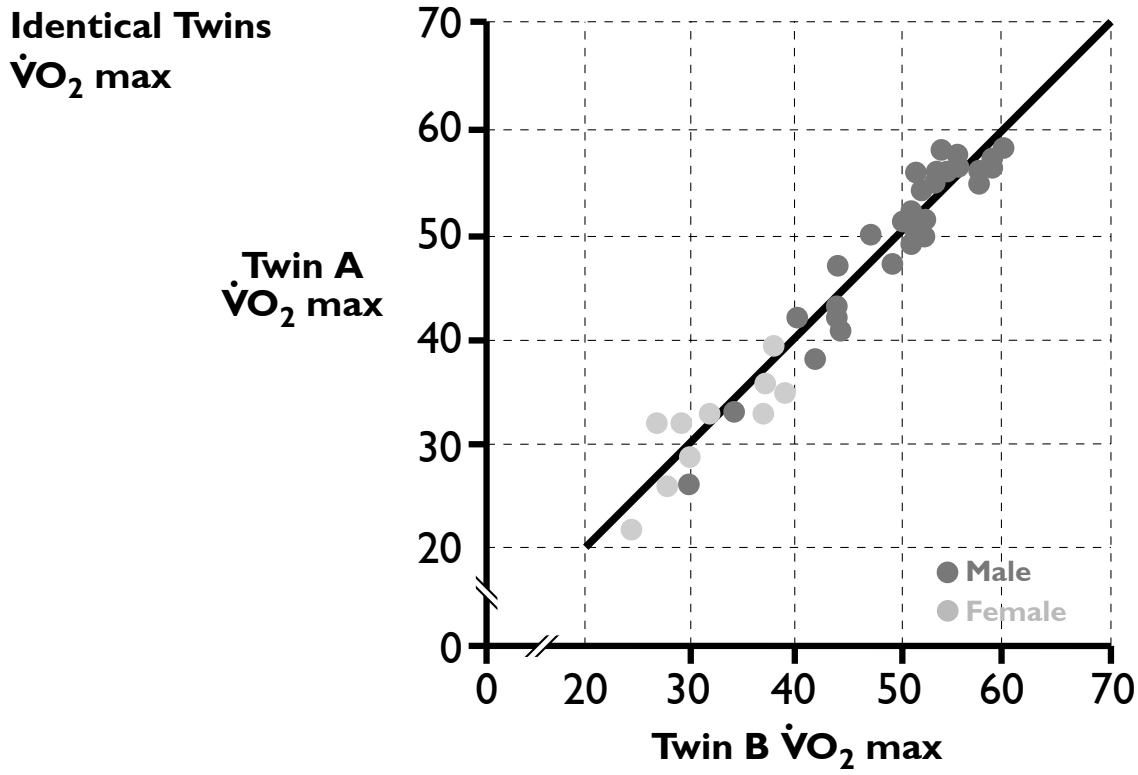
*Cycle Ergometer

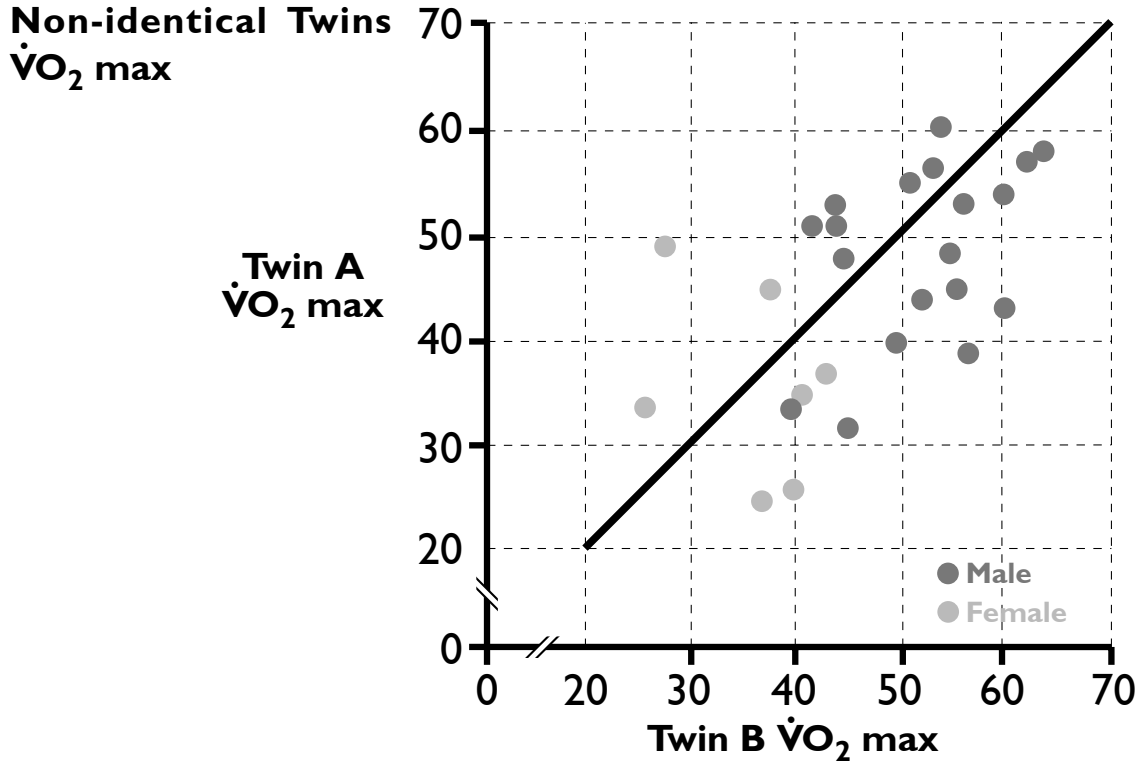


Response of some physiological measures to increasing sub-maximal work rates



Correlations of VO_2max between members of pairs of twins

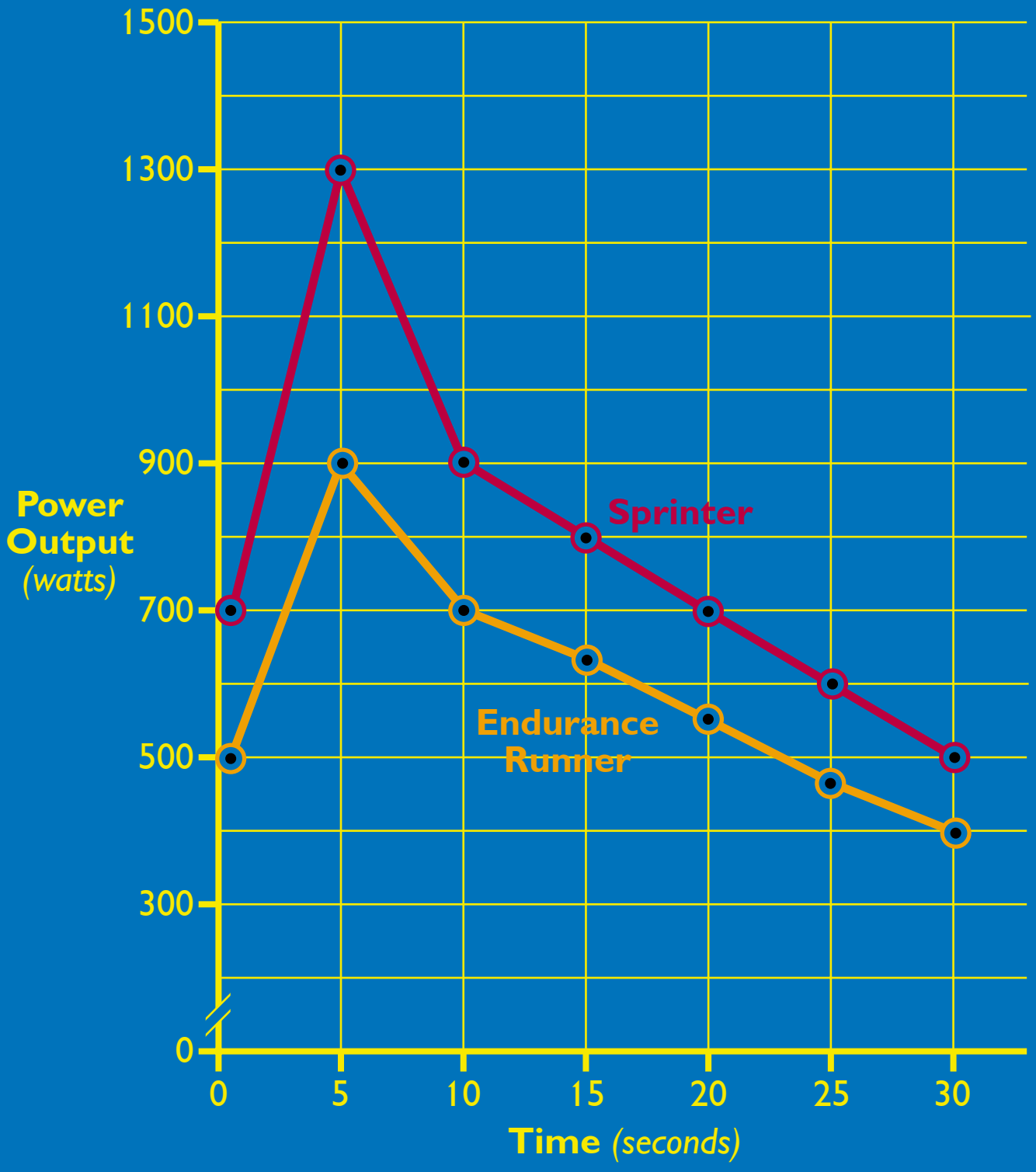




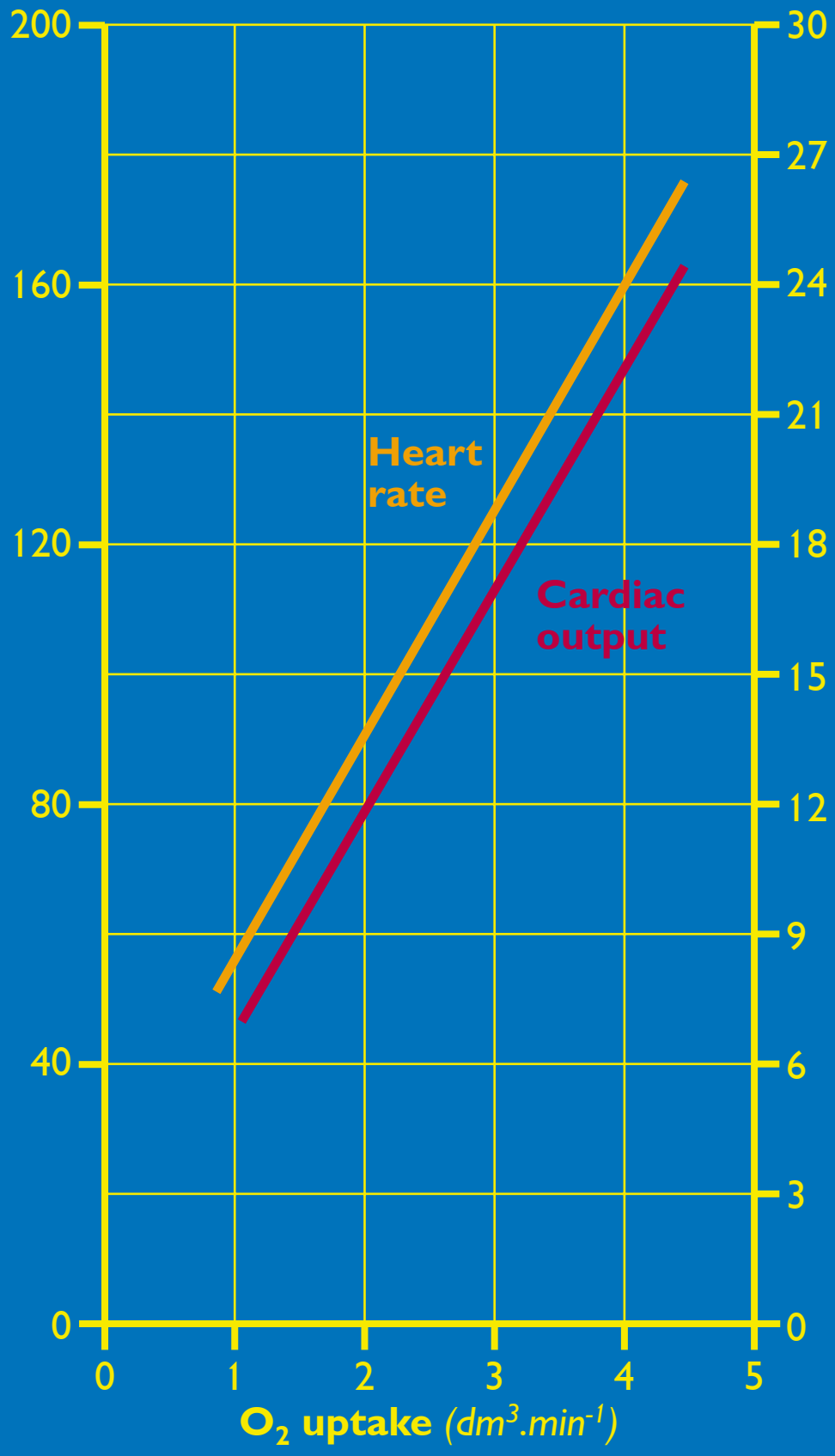
APPENDIX I

Full Colour Versions 1 - 18

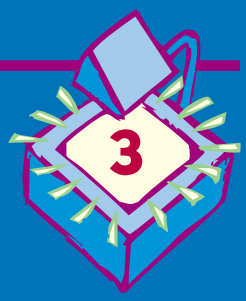
Power output of a sprinter and an endurance runner during a Wingate test on a cycle ergometer.

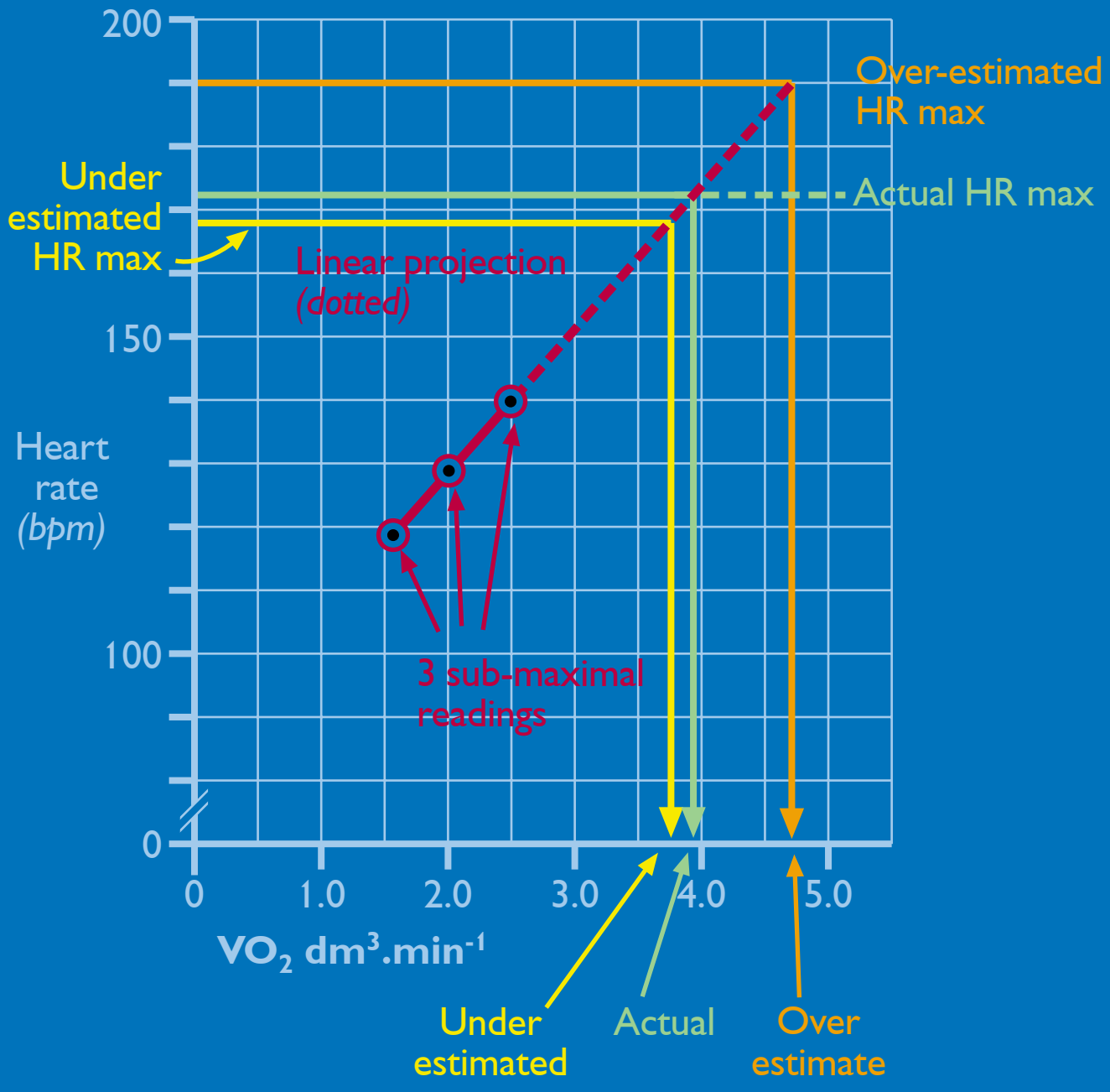


Ideal linear relationship between heart rate and oxygen uptake, and cardiac output and oxygen uptake, at sub-maximal work rates.

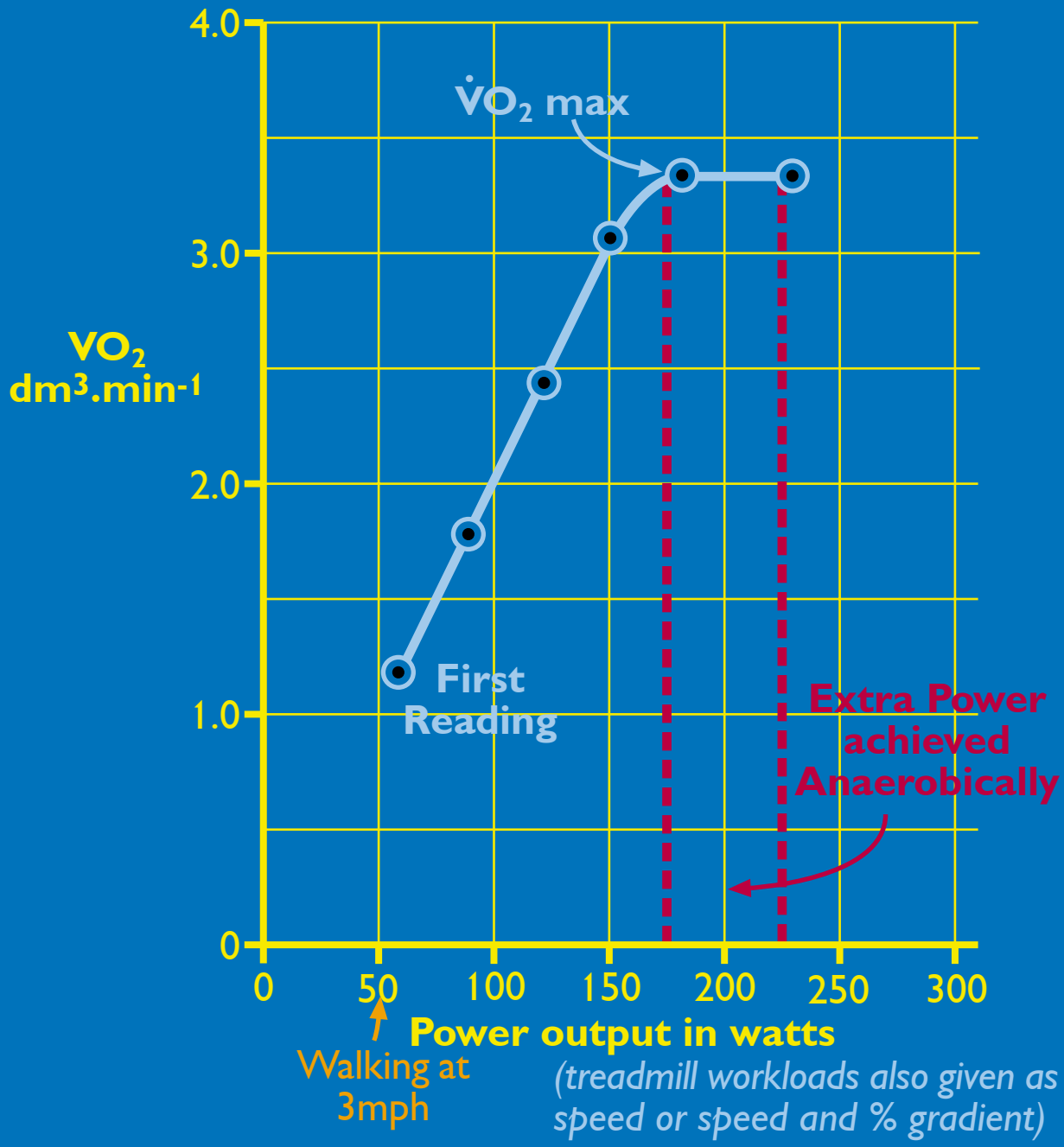


Projection of maximum oxygen uptake from heart rates in a progressive incremental sub-maximal test.





Oxygen uptake in relation to work output in a progressive incremental treadmill test.



2 minutes at 60 watts and then increments of 30 watts every 2 minutes.
A watt is the unit of rate of work or power 1w = $1J.s^{-1}$.
A reasonably fit person could maintain about 200 watts for an hour.
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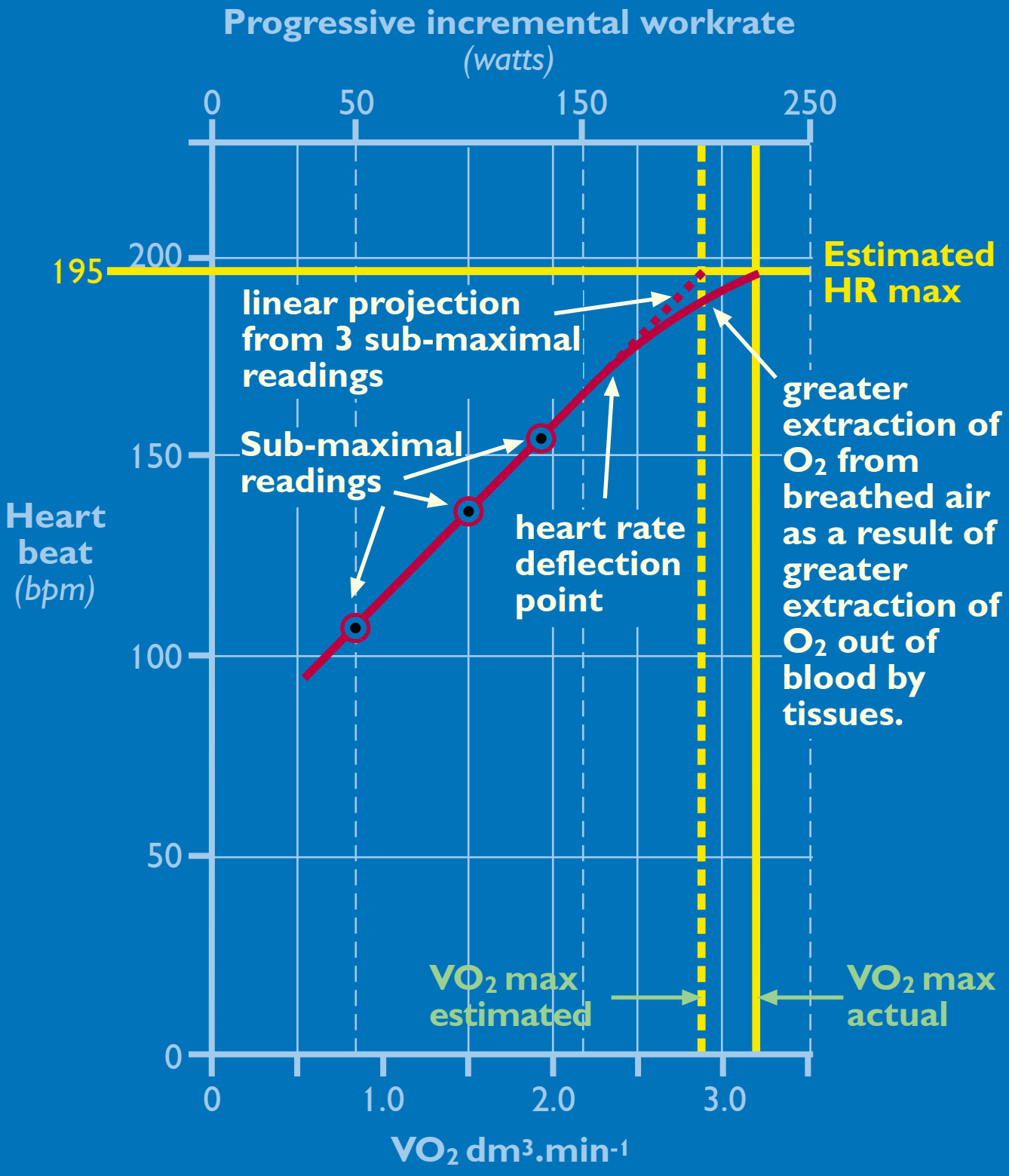
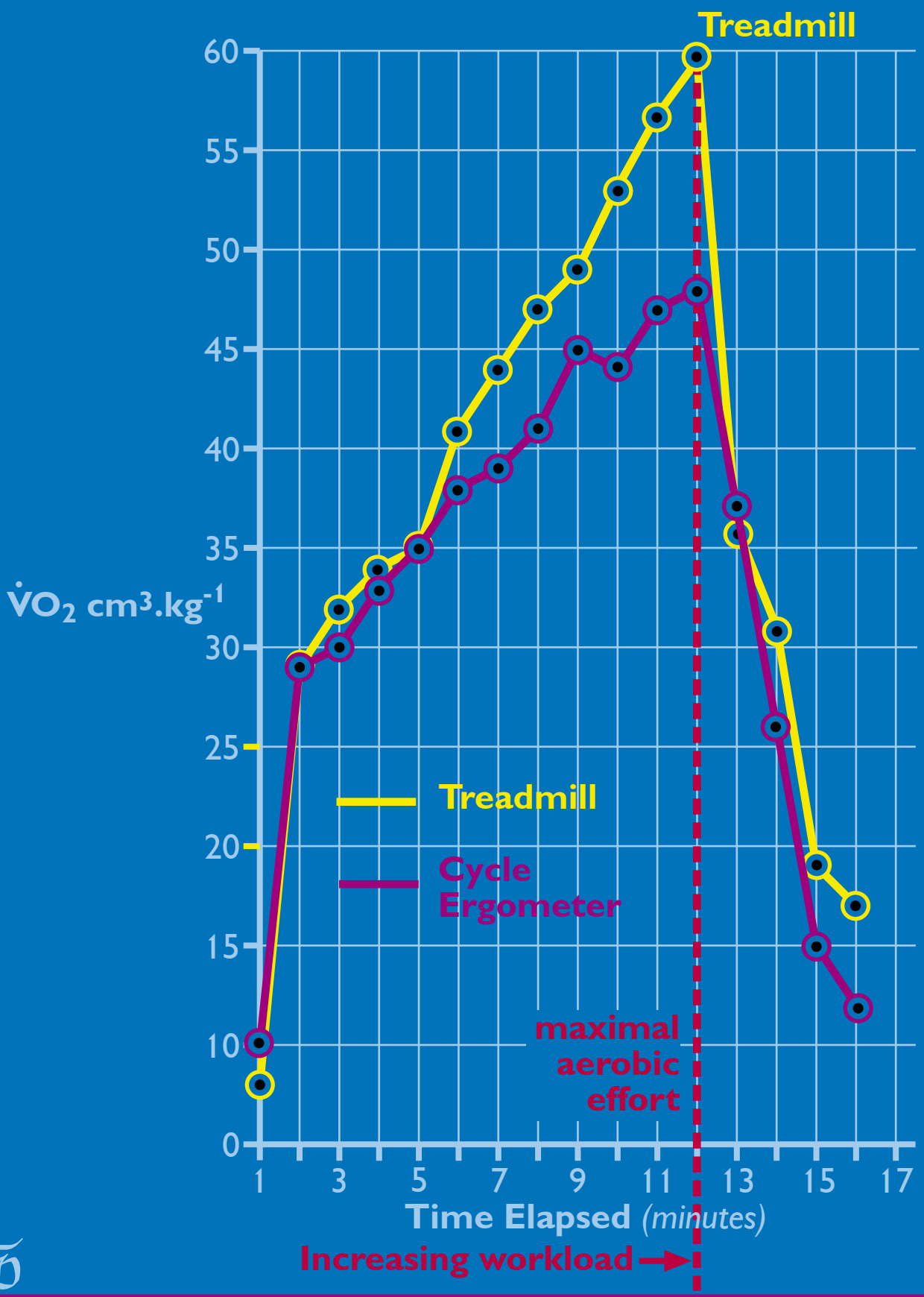
Peak power outputs are as high as 1500 watts.

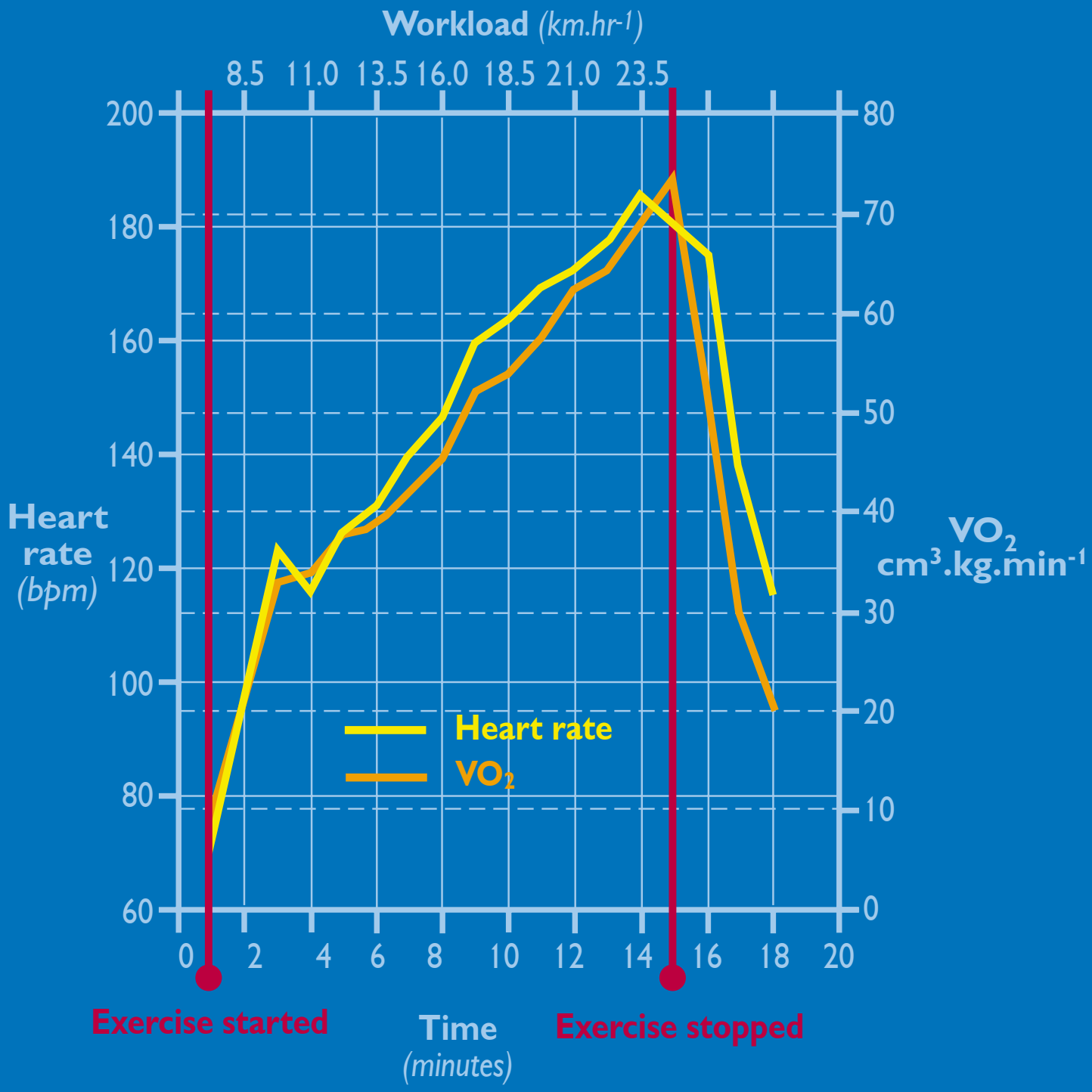
The relationship between heart rate, work rate, and oxygen uptake.



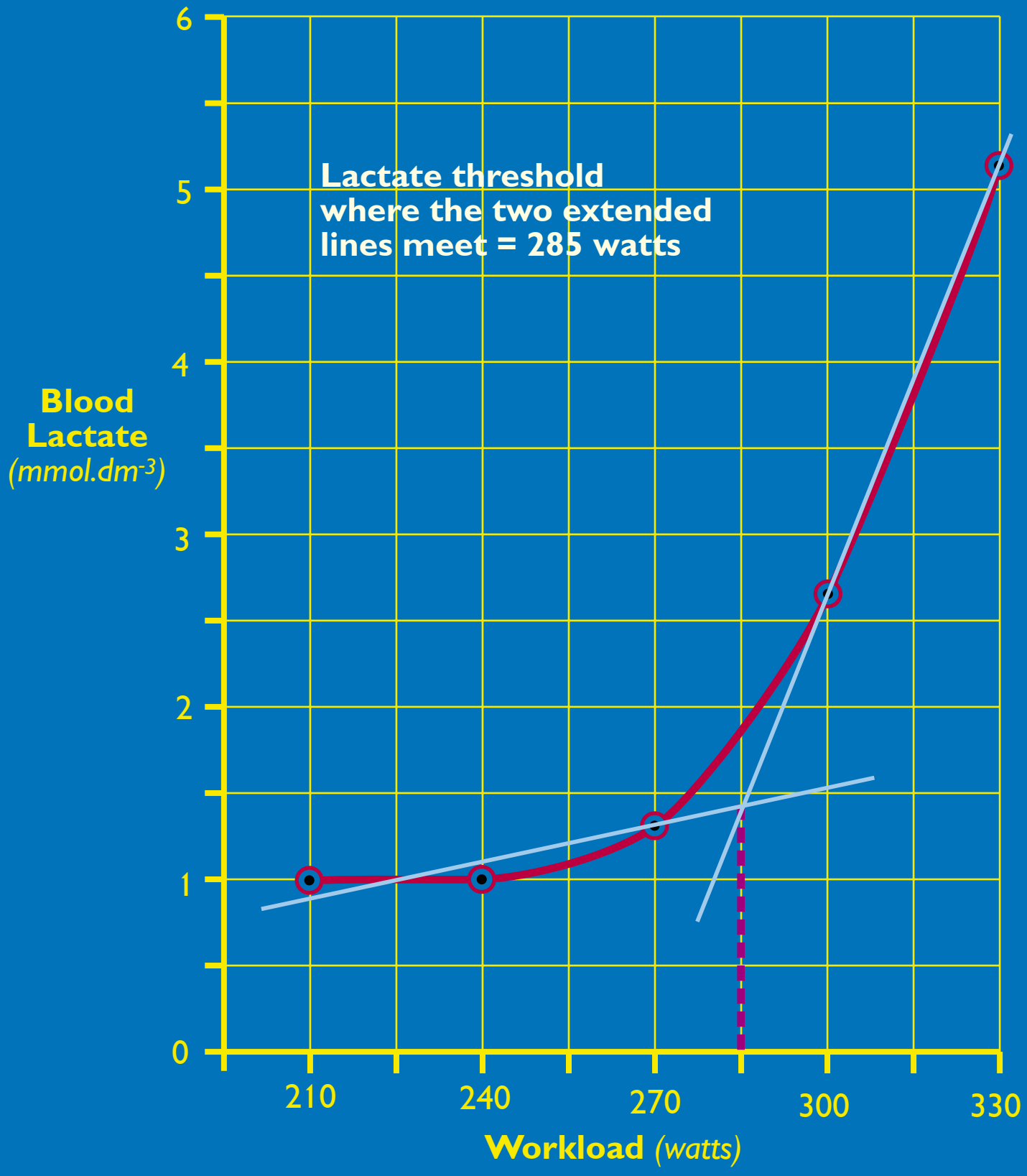
O_2 uptake against time in a single subject during a progressive maximal test on (i) a treadmill, and (ii) a cycle ergometer.



Heart rate and oxygen uptake of a middle distance runner performing a maximal treadmill test.

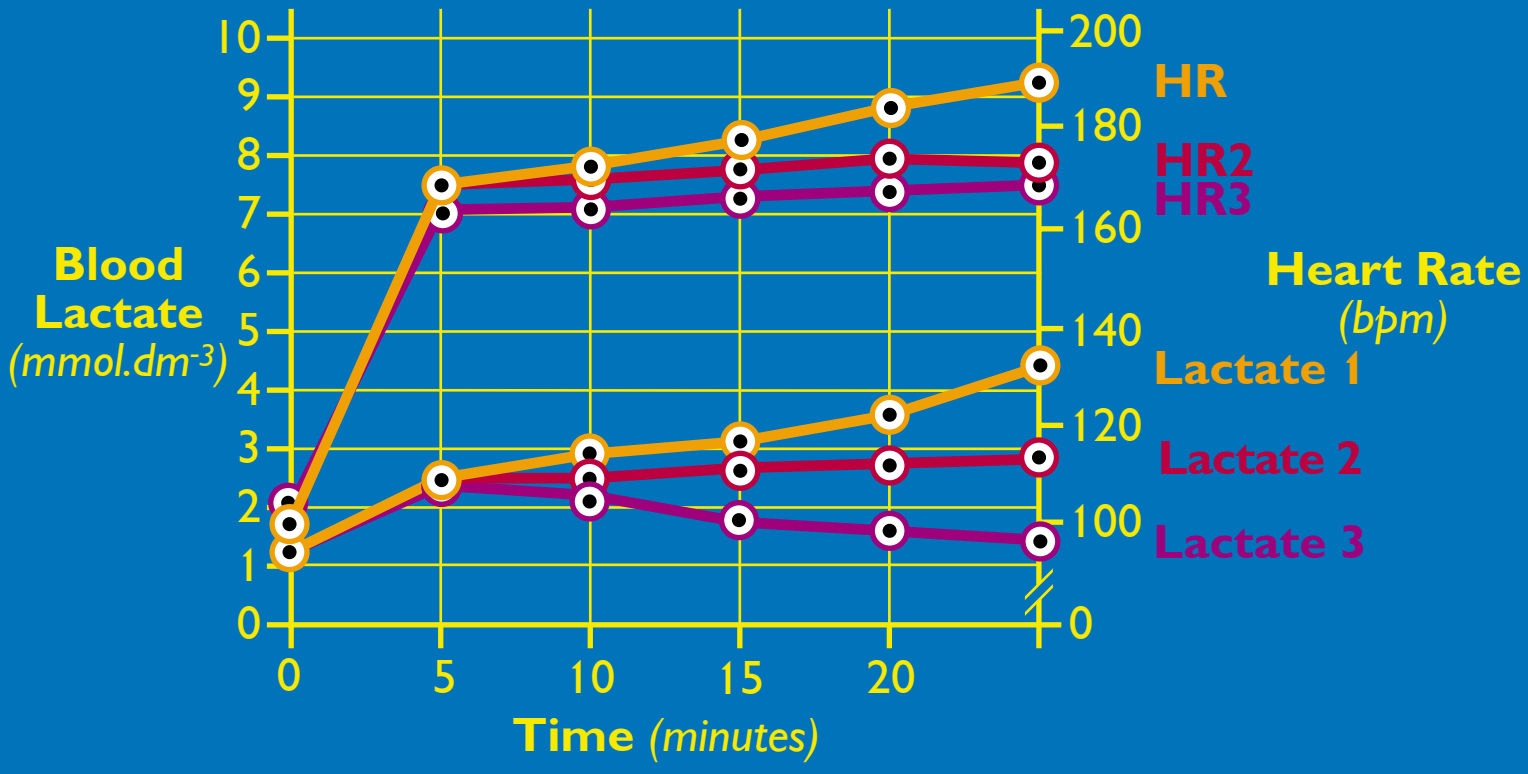

Workload (km.hr-1)
8.5 11.0 13.5 16.0 18.5 21.0 23.5
200 180 160 140 120 100 80 60
80 70 60 50 40 30 20 10 0
Heart rate (bpm)
VO2 cm3.kg.min-1
Heart rate
VO2
0 2 4 6 8 10 12 14 16 18 20
Exercise started
Time (minutes)
Exercise stopped

Determination of Lactate Threshold in a progressive incremental test by projection.



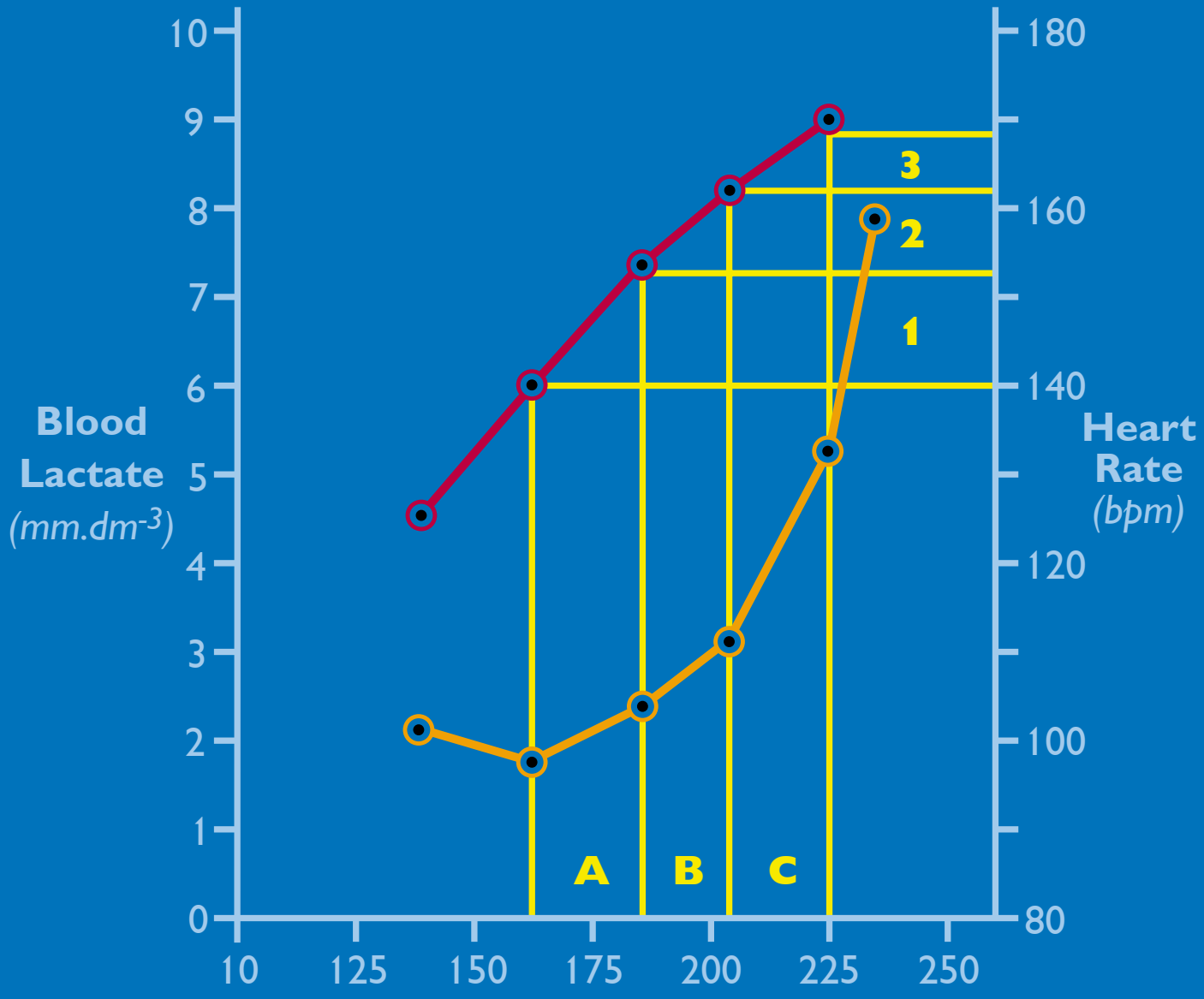
Determination of Maximum Lactate Steady State in a progressive incremental test.

Graph showing the Determination of Maximum Lactate Steady State of an Athlete.



Progressive Incremental Work Load	Time in minutes	0.0	5.0	10.0	15.0	20.0	25.0
Load 1	Lactate 1	1.31	2.49	2.50	2.67	2.72	2.80
	HR 1	100	169	171	173	174	173
Load 2	Lactate 2	1.31	2.50	2.90	3.10	3.54	4.36
	HR 2	104	170	173	178	185	190
Load 3	Lactate 3	1.31	2.40	2.22	1.80	1.60	1.40
	HR 3	104	166	165	167	168	169

Determination of heart rate training zones from blood lactate measurements during progressive incremental work loads.



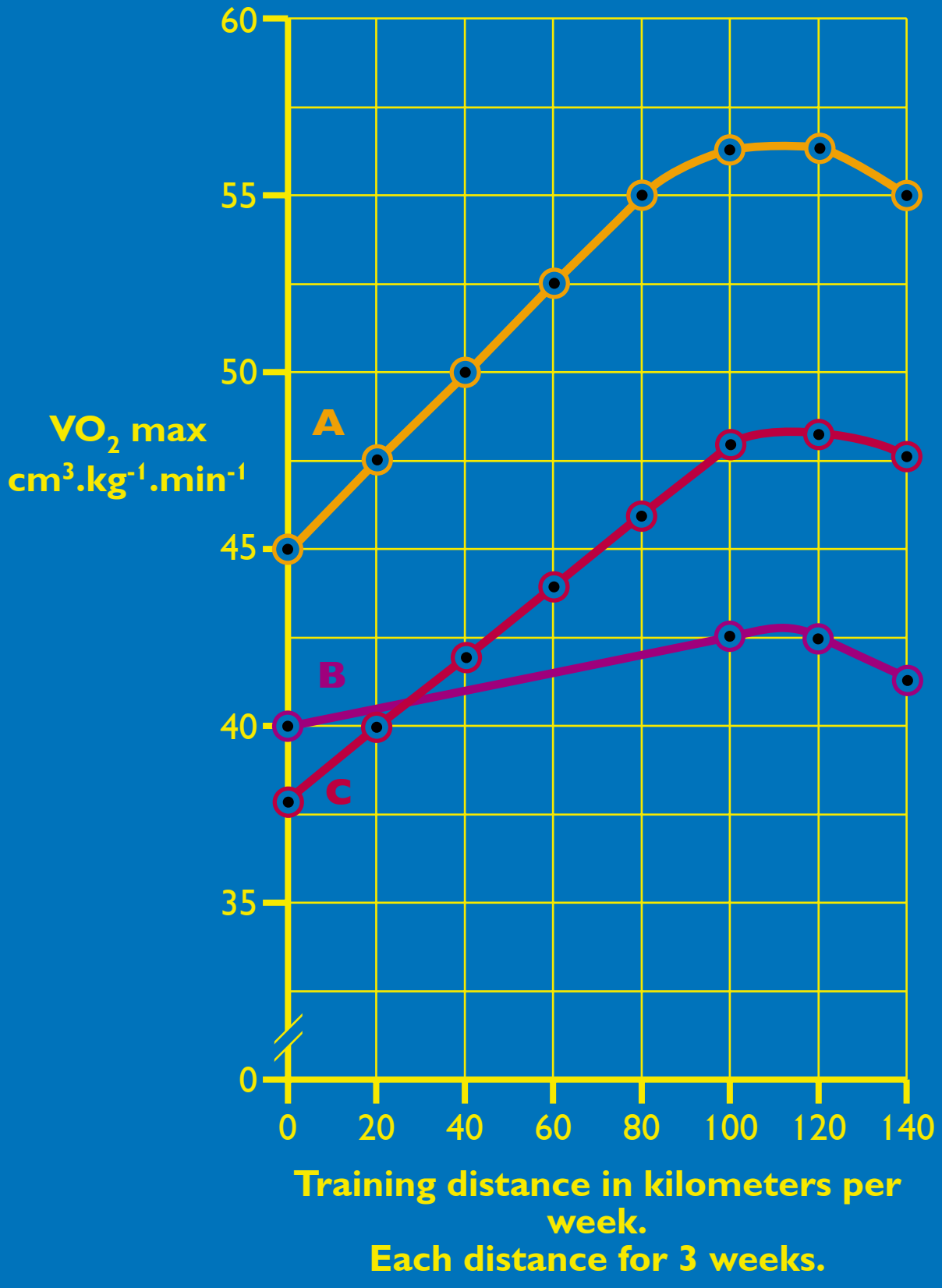
Power Output *(watts)*
during progressive incremental test

4 minute efforts at each work load
Lactate sampled
30 seconds rest
4 minutes at next work load

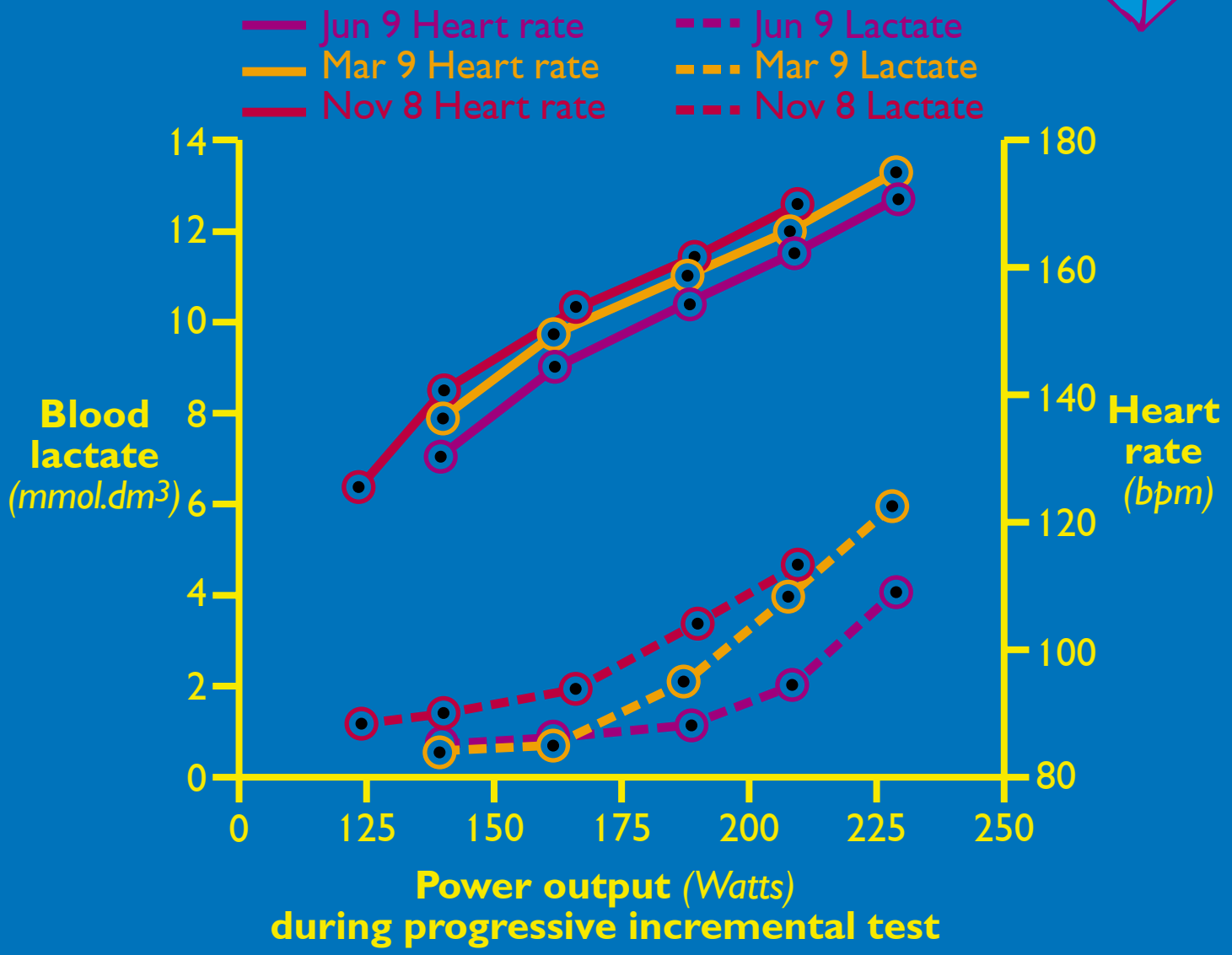
A - base endurance steady state
B - upper endurance steady state
C - anaerobic threshold zone

1
2
3
} corresponding training heart rate zone

The effect of endurance training on maximal oxygen uptake.



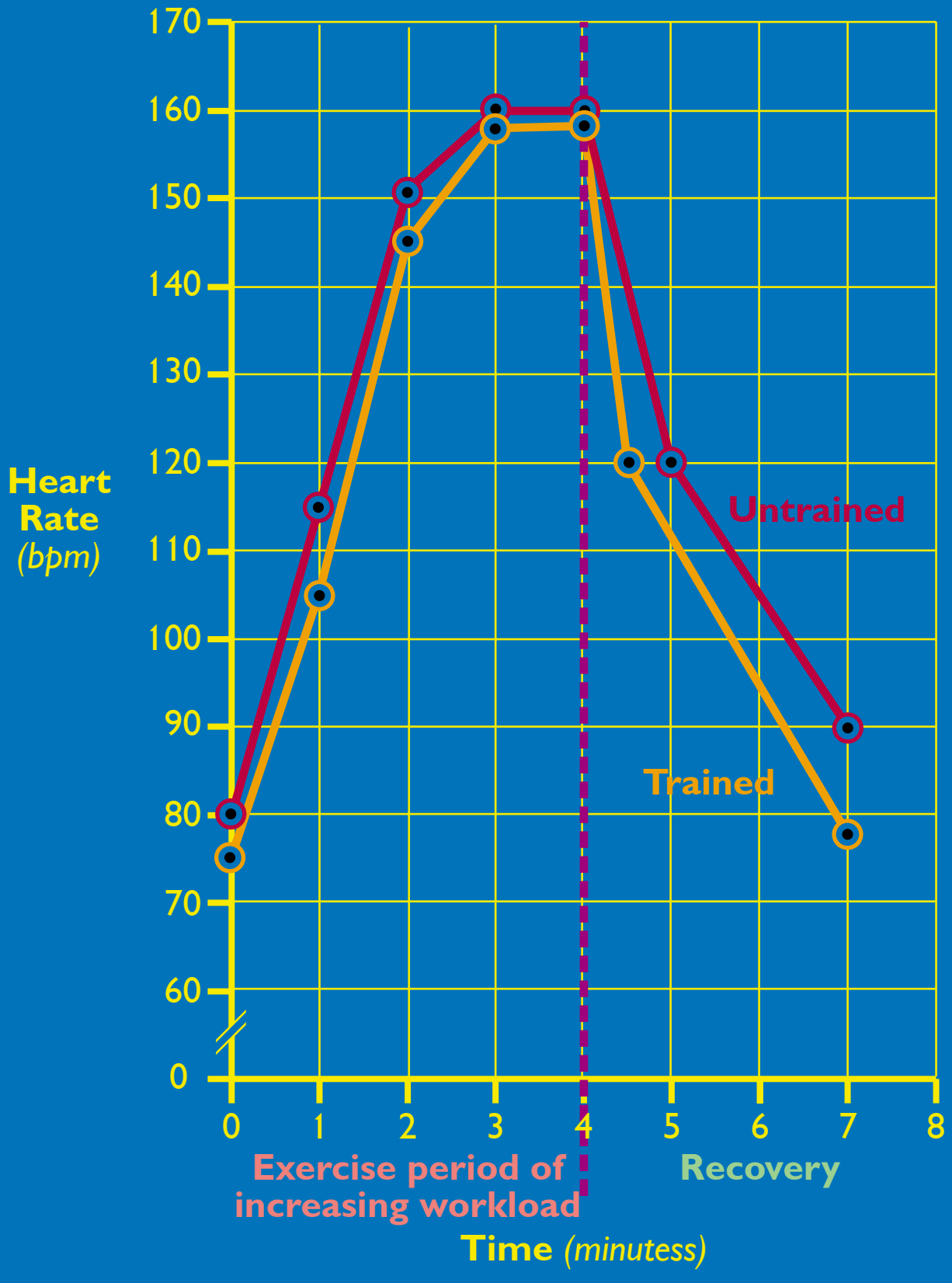
Fitness progression of an athlete at 3 month intervals.



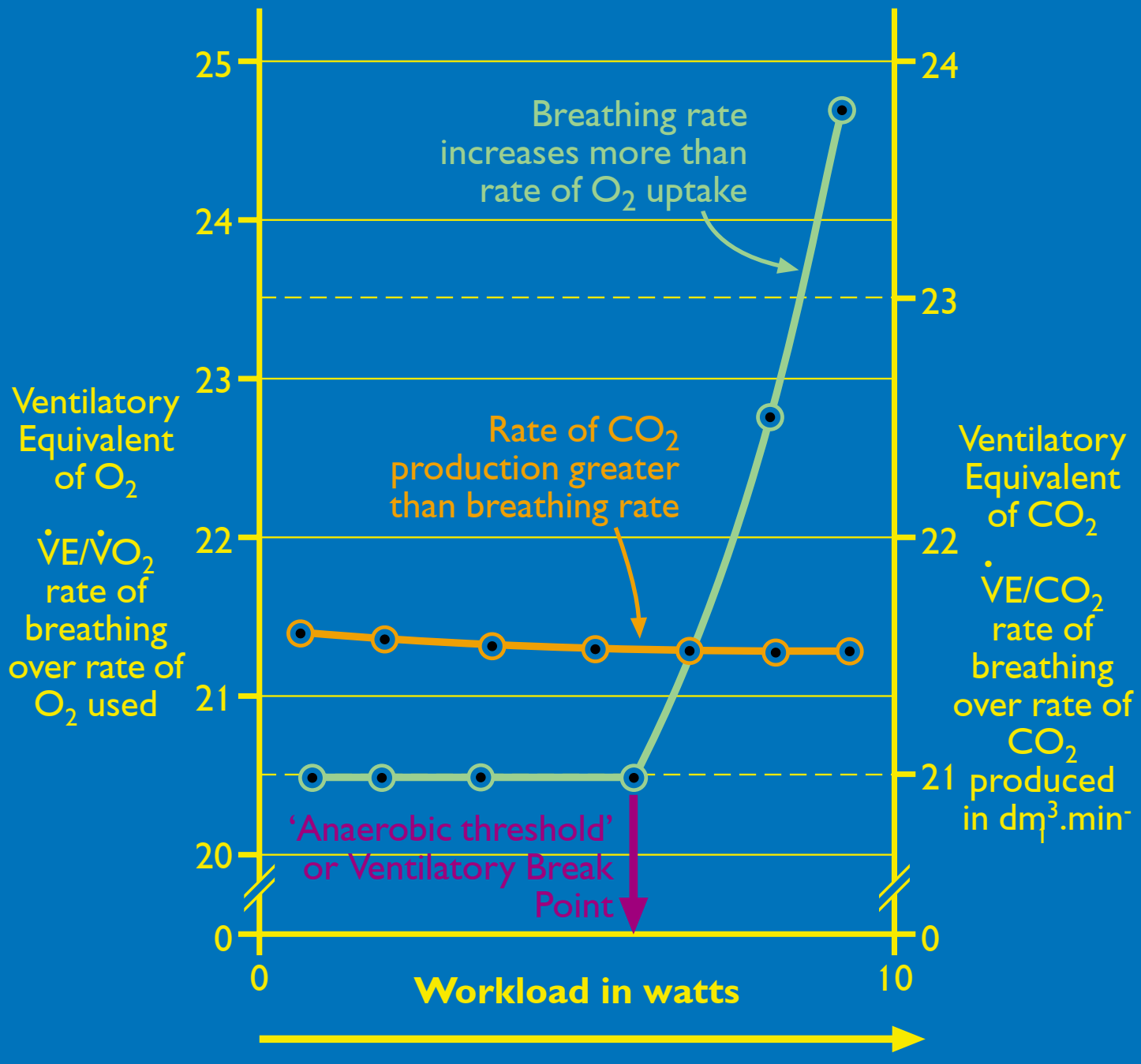
Step Test	Workload	1	2	3	4	5
Jun 99	Watts	140	162	188	208	228
	Lactate	0.70	0.90	1.20	2.06	4.09
	Heart rate	131	145	155	163	171
Mar 99	Watts	140	162	188	208	228
	Lactate	0.60	0.70	2.11	3.92	6.00
	Heart rate	137	150	159	166	175
Nov 98	Watts	124	140	166	189	209
	Lactate	1.22	1.49	2.00	3.40	4.70
	Heart rate	126	141	154	162	170

4 min efforts at each workload, lactate sampled, 30 sec rest, 4 min at next workload....

Effect of training on post-exercise recovery heart rates in a single subject.

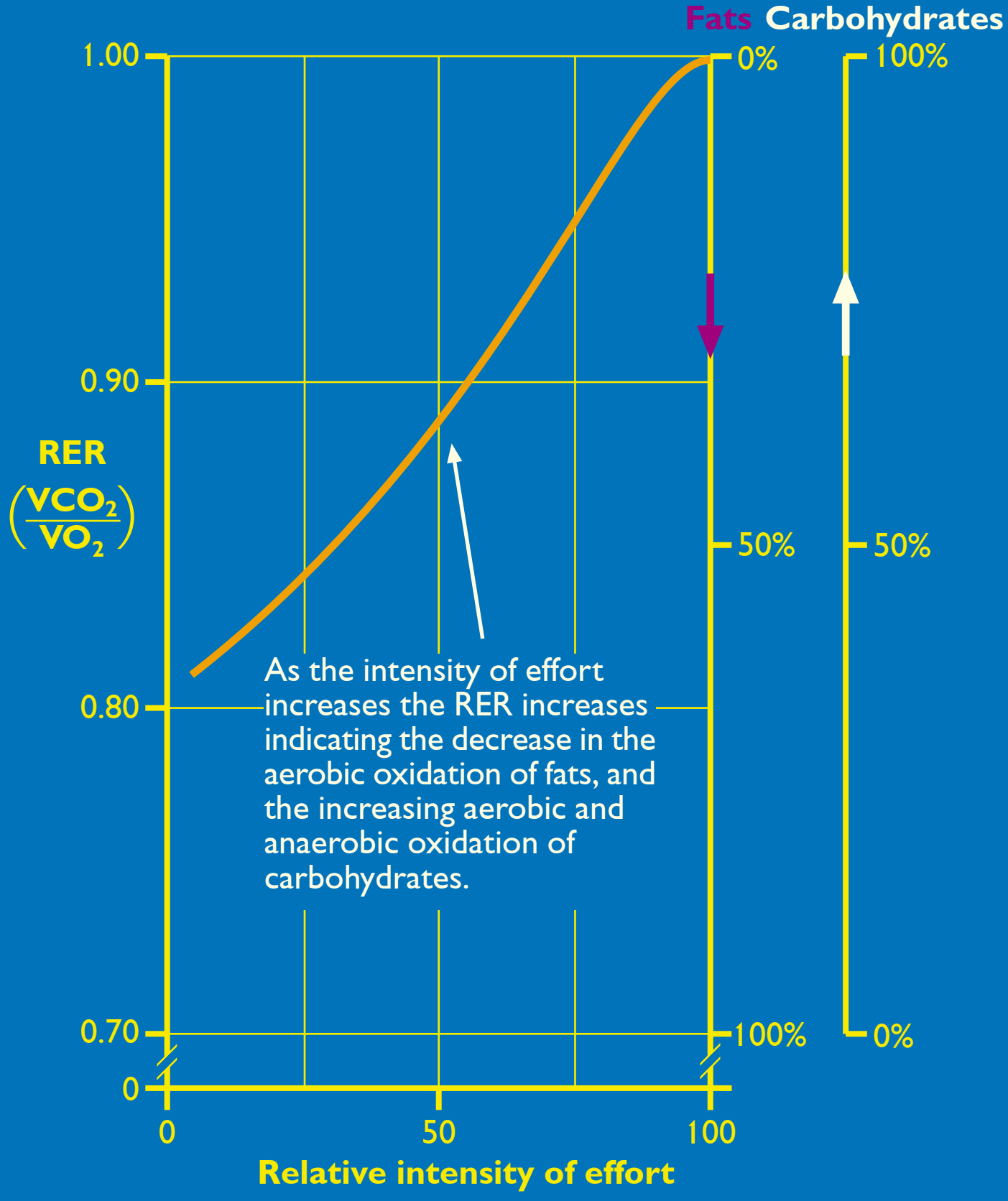


The ventilatory break point or anaerobic threshold.



These curves reflect the fact that CO_2 production and an associated drop in blood pH *(increase in acidity)* are the main stimuli to increase the ventilation rate.

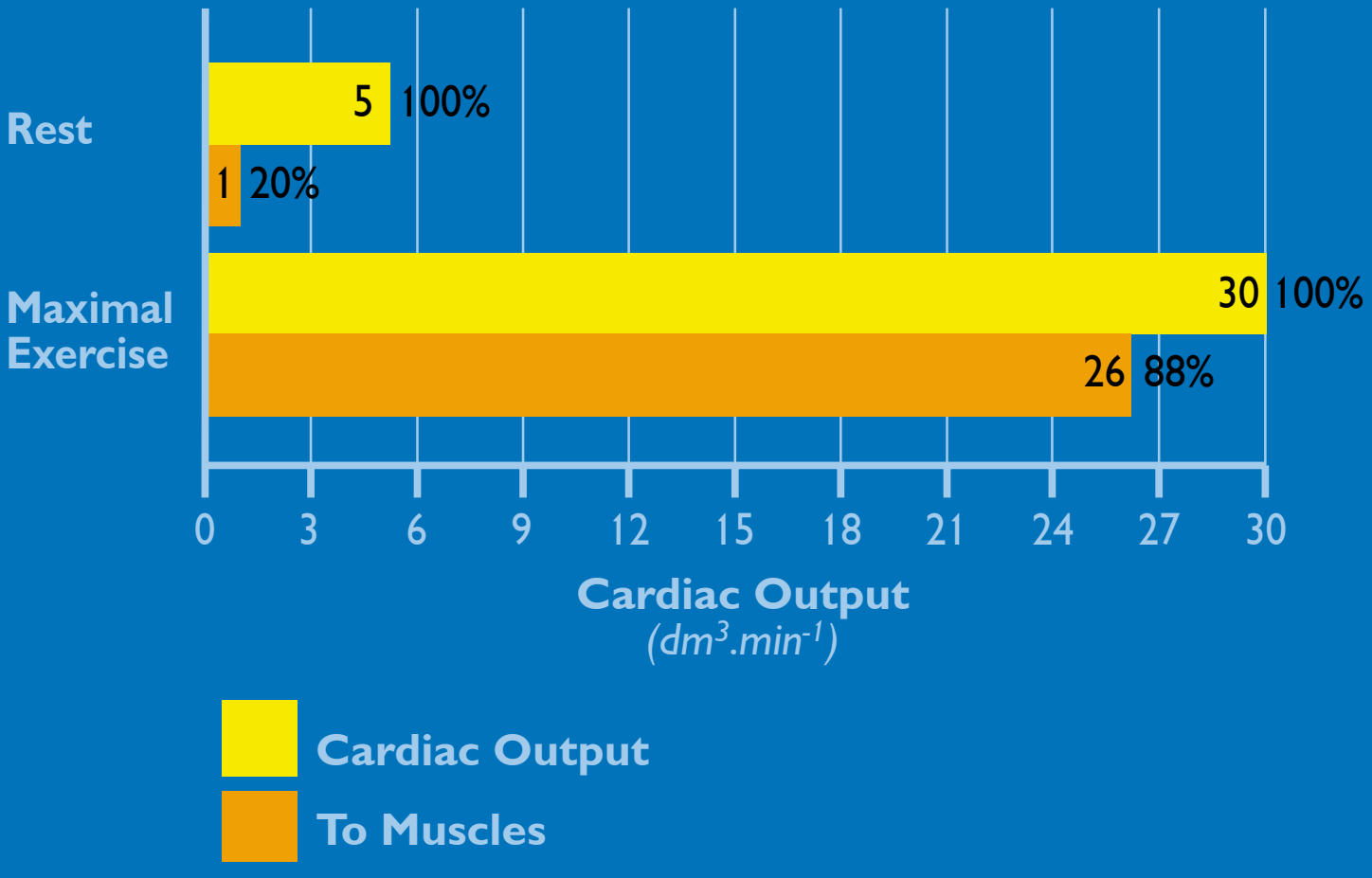
Estimation of the respiratory substrates and the type of respiration from the Respiratory Exchange Ratio *(RER)* in relation to intensity of effort.



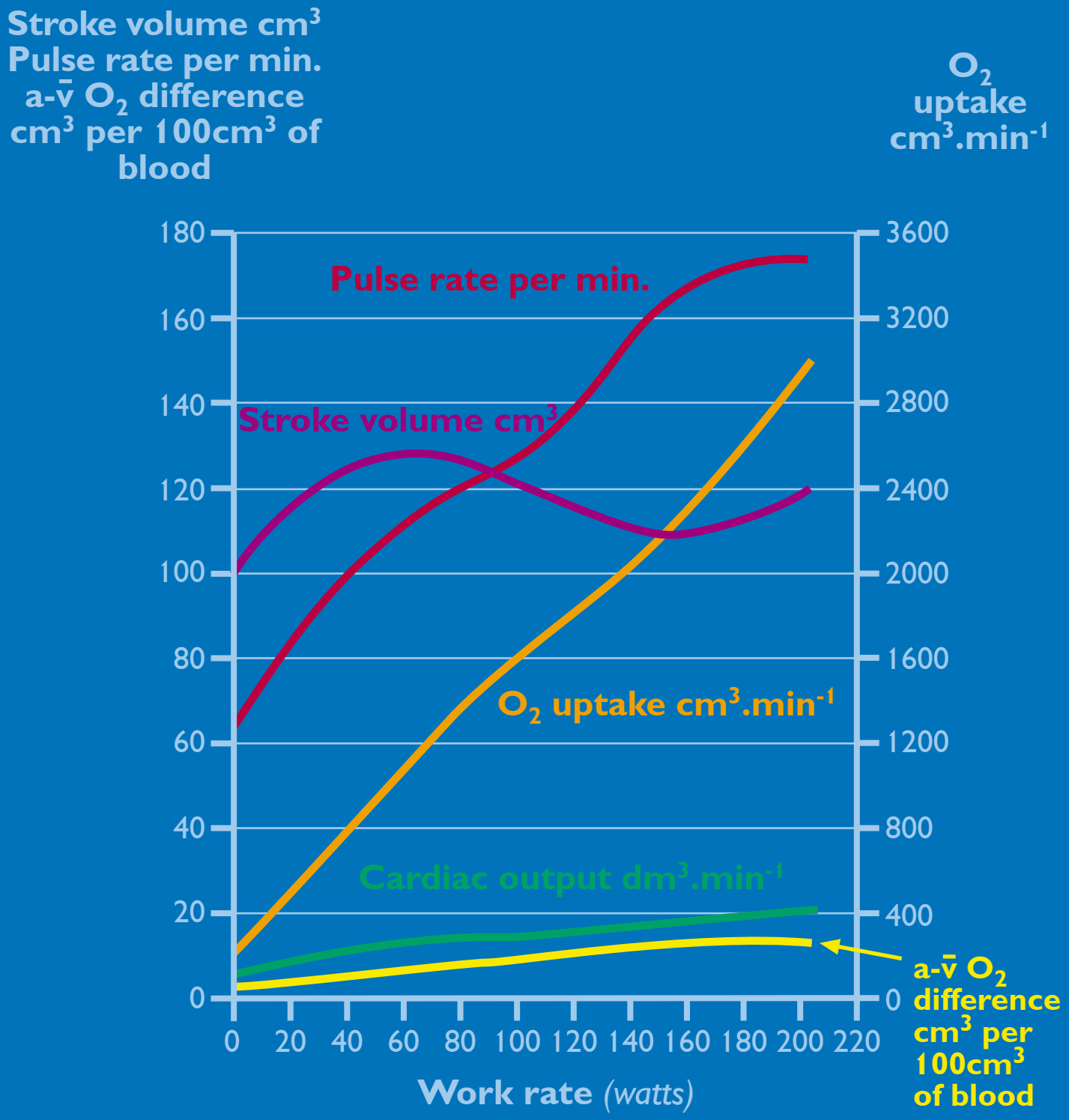
Estimated Blood flow in cm^3 per minute to different organ/systems in a trained male at rest and during maximum effort.

Organ System	At Rest	%	Max Effort*	%
Skeletal muscle	1000	20	26000	88.00
Coronary vessels	250	5	1200	4.00
Skin	500	10	750	2.50
Kidneys	1000	20	300	1.00
Liver & gut	1250	25	375	1.25
Brain	750	15	750	2.50
Whole body	5000	100	30000	100.00

*Cycle Ergonometer

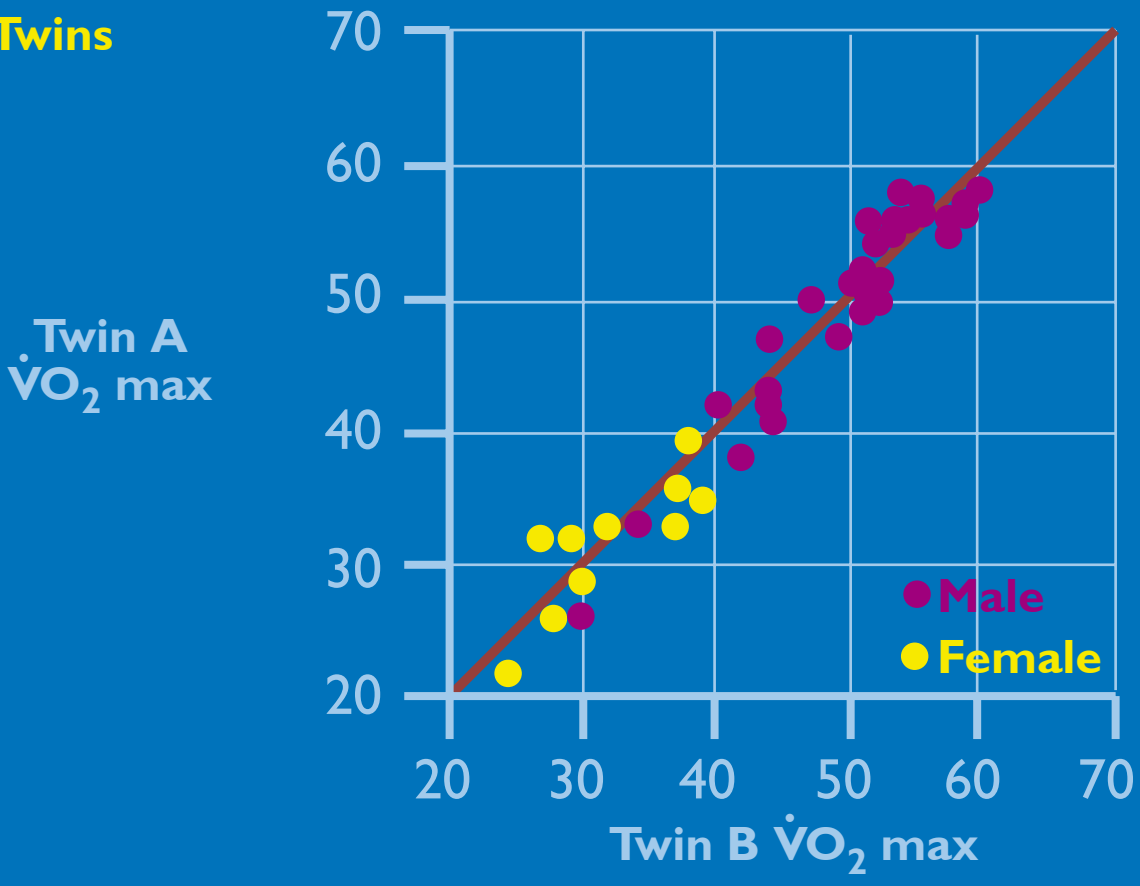


Response of some physiological measures to increasing workrate



Correlations of $\dot{V}O_2$ max between members of pairs of twins.

Identical Twins
$\dot{V}O_2$ max



Non-identical Twins
$\dot{V}O_2$ max